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THE BLACK HILLS AS A "GREEN AREA" SINK FOR ATMOSPHERIC POLLUTANTS (First Annual Report)

By: Briant L. Davis, Donald N. Blair,
L. Ronald Johnson, and Steven J. Haggard

Prepared for:

U. S. Department of Agriculture
Rocky Mountain Forest and
Range Experiment Station

Cooperative Agreement No. 16-419-CA

Institute of Atmospheric Sciences

South Dakota School of Mines and Technology

Rapid City, South Dakota 57701

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ABSTRACT

A study of small particle pollution in the Black Hills area of western South Dakota has been initiated. The sampling was conducted over thirteen hills and surrounding plains stations for a period of twelve months using a Gardner small particle counter. The concentrations of both Aitken and near-CCN particles were obtained and supplemented by meteorological observations. The results of the analysis of these data indicate that the Black Hills area is a significant reservoir of clean air and that the observed low particle concentrations are the result of a) the natural decrease in concentration with elevation, b) the reduction in count due to frequent precipitation events over the Black Hills; and c) the true "green area" effect due to the particle removal mechanisms of vegetation. Several tests were developed to assess the magnitude of the green area effect. After corrections were applied for elevation changes, precipitation scavenging, and local pollution sources, the present analysis suggests the presence of significant particulate filtering by the heavy vegetation covering of the Black Hills. Additional data are needed to increase our understanding of the green area effect, but present indications are that a reduction in particulate concentration by as much as a factor of two (relative to plains concentrations) may be taking place as a result of these filtering processes.

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1. INTRODUCTION

1.1 The Significance of the Green Area Effect

In an early paper dealing with the significance of condensation nuclei in atmospheric pollution, Neuberger (1948) briefly mentioned the importance of vegetation as filters for cleaning up the atmosphere. In a later study (Neuberger, 1967) the efficiency of both coniferous and deciduous trees in cleaning up ragweed pollen and Aitken nuclei was documented. The reality of vegetation as a sink for both gaseous and particulate matter is indicated in the studies of Bennett *et al.* (1973), Hill (1971), and Smith (1974). In the latter study, the significance of the degree of atmospheric pollution loading upon vegetation was assessed, leading to the development of several classes of pollutant ecosystem interactions. The results of this study included an assessment of the pollution on the well being of the plants and included a discussion of the various morbidity and mortality problems that occur when pollution loading exceeds a certain level. The sensitivity of vegetation to SO_2 and NO_2 was similarly studied by Hill *et al.* (1974). An examination of the actual effects of particulates on the stomatal diffusion process was undertaken by Ricks and Williams (1974), with the result that changes in gaseous transfer were observed with particle occlusion of the stomatal pores. One should refer to the excellent review by Smith (1974) for other specific toxological effects of pollutants on vegetation.

Related pollutant-sink studies include: the effective removal of certain pollutants such as ethylene, sulphur dioxide, and nitrogen dioxide by soil (Abeles, 1971), and the production of hydrocarbons such as terpenes from vegetation (Rasmussen, 1972).

1.2 Previous Systematic Studies

Actual documentation of the green area effect in urban areas is limited, but a study of Hyde Park in London, England (Meetham, 1964) indicated a 27% reduction in smoke concentration in the vegetated area of the park. A similar study in Cincinnati (Bach, 1971) demonstrated a cleanup effect with a slight "particle shadow" noticeable downwind of the green area with an easterly airflow.

1.3 Scope of the Present Study

To our knowledge there has not been a systematic study of particulate removal over a large green area based on background levels of particulate concentrations. Such a study encounters difficulties from several standpoints:

A. Such a study must be undertaken in a region where large urban pollution sources do not obscure the assumed much lower baseline counts.

B. The contrast between the green area and surrounding areas is much reduced by virtue of the lower level of background counts experienced.

C. Effects such as variability of weather processes, temperature, elevation, precipitation scavenging, and topography all must be considered in order to obtain a proper assessment of green area phenomenon.

The Black Hills of western South Dakota and eastern Wyoming represent as nearly an ideal arrangement for such a study as can be obtained anywhere in the continental United States. This statement can be justified on the basis of precautionary statements enumerated above. There are no large urban metropolitan areas within 400 miles of the Black Hills. Rapid City, population 46,000, constitutes the largest pollution source and lies on the eastern slope of the Black Hills.

The dome-like topography of the Black Hills dictates a need for certain corrections and precautions in the data handling, but the uniformity of the dome-like structure and the topographically controlled extent of vegetation should make the required corrections relatively uniform. Of greatest concern is the variability of the weather pattern throughout the area and the obvious scavenging effect of the more frequent precipitation overlying the Black Hills in comparison to the surrounding areas.

In spite of the obvious difficulties in conducting such a study, particularly in view of the existing low background level of Aitken and larger particle concentrations, the study has been undertaken in an attempt to document a large scale green area effect. The effect is being studied with respect to the Aitken and near-CCN particulate concentrations; there have been no studies to determine SO_2 or NO_x gaseous absorption processes.

2. OBSERVATIONAL TECHNIQUES AND ANALYSIS

2.1 Equipment

Figure 1 is a photograph of a modified Gardner condensation nucleus counter. The principle of this counter is presented in detail in the review of Davies (1974), and from Mason (1971, p. 31). In brief, a parcel of air is drawn into a chamber and allowed to rest for several seconds in the presence of a wet blotter paper. While this air sample is being humidified, an adjacent chamber is evacuated to a prescribed pressure level and sealed. The measurement of particle concentration is accomplished by connection of the two chambers and a resulting expansion of the moist air parcel. Condensation upon the particles is monitored by a photoelectric cell, the readout of which is a calibrated function of the light transmissivity in the chamber. The signals from the photoelectric cell are displayed in terms of particle concentration on the zero-compensated voltmeter. The original equipment was supplied with only an imprecise small vacuum gage by the manufacturer. In the modified device, a high precision vacuum gage was added in place of the original and a bleed valve system was incorporated to eliminate pressure shock and momentary condensation of moisture within the sensitive gage mechanism. With the more accurate gage assembly, a pressure differential as small as 5 torr (which produces saturation ratio values as small as 1.02) can be estimated.

Emphasis in this study is on the measurement of Aitken nuclei (all particles of $r < 0.1$ mμ) and of what we shall define as "near-CCN" (CCN = Cloud Condensation Nuclei). The former are obtained by creating a maximum expansion ratio for the instrument, whereas near-CCN are particles activated at S = 1.04 (saturation ratio). Near-CCN aerosols therefore contain smaller-sized particles in addition to true CCN which are activated at $S \leq 1.01$. The calculated saturation ratios obtained for a given pressure differential in the range applicable to this study are given in Fig. 2.

Other equipment used included a small hand anemometer, a compass, and a sling psychrometer.

2.2 Procedures

Standardized field procedures were maintained for all sampling activities. The wet and dry bulb temperatures, wind direction and velocity, and counts at four different pressure differentials were recorded at each of thirteen field stations. The sky conditions, presence of precipitation, and amount of snow cover were also noted. Other comments included the presence of possible pollution sources

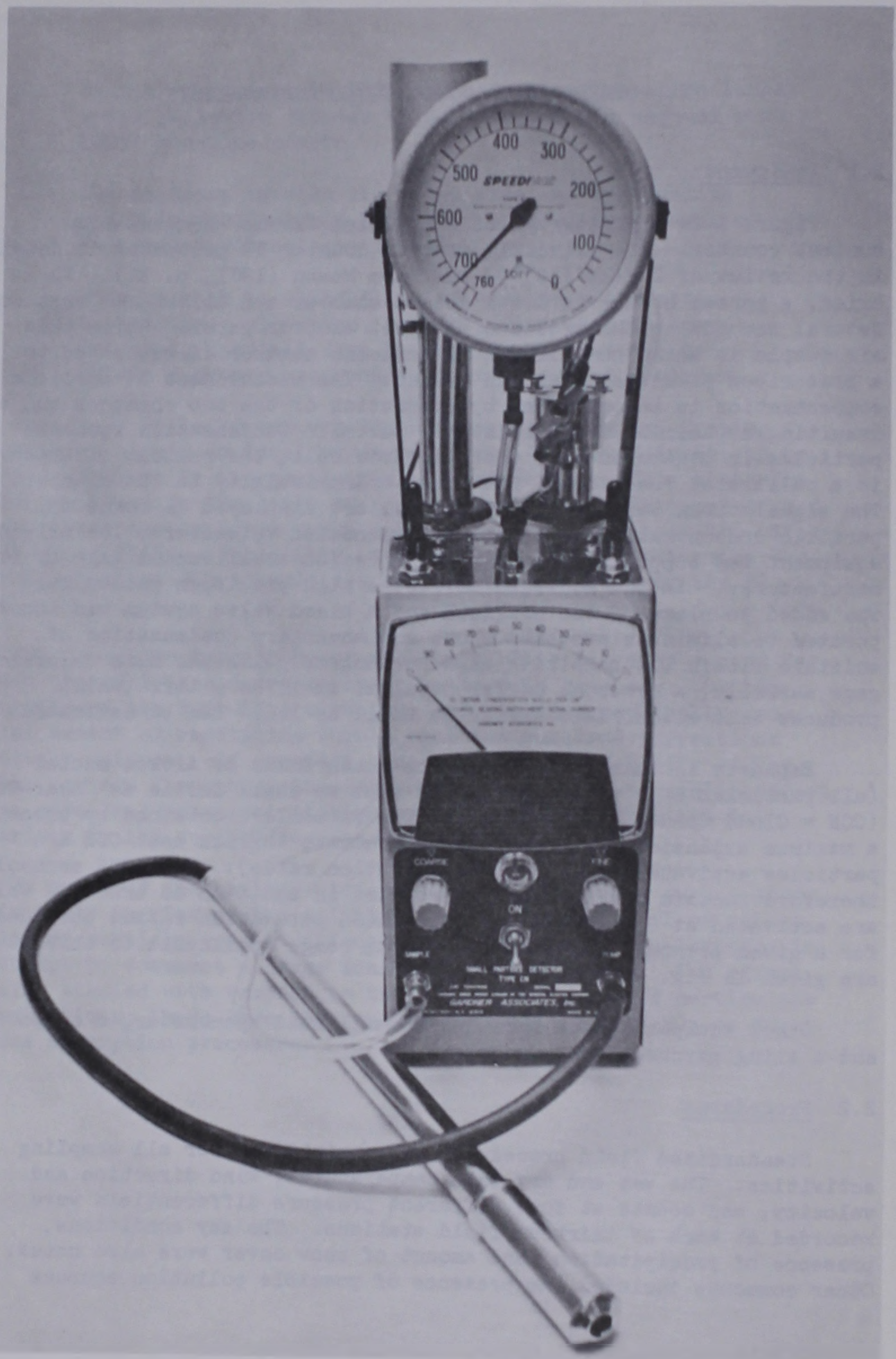

Fig. 1. Close-up of Gardner small particle counter showing large vacuum gage and associated bleed system. Instrument is about 45 cm high.

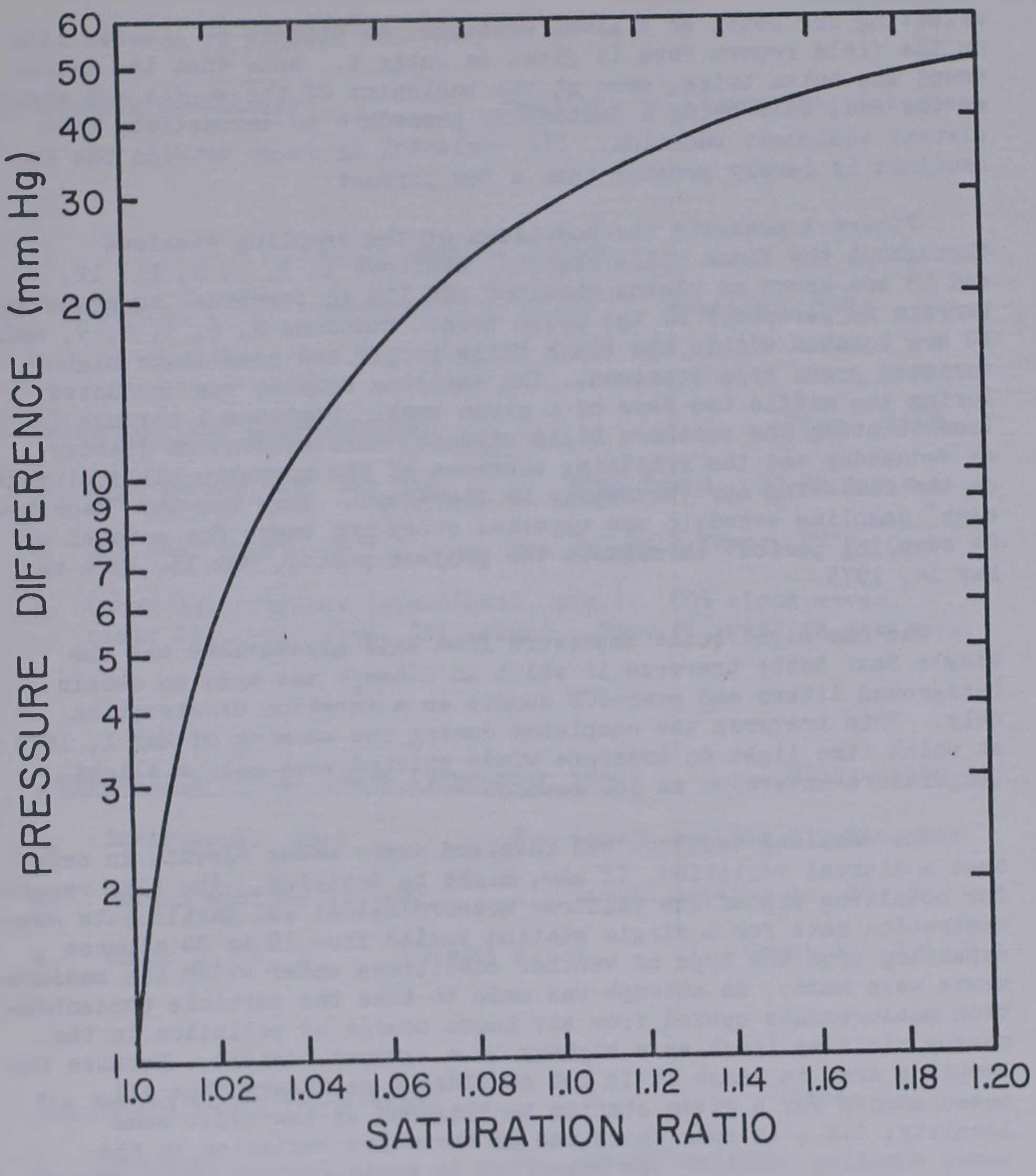

Fig. 2. Saturation ratio from pressure difference for small particle counter for the range of near-CCN particles.

affecting the count at a given station. An example of entries made on the field report form is given in Table 1. Note that the Aitken count was taken twice, once at the beginning of the series and again at the end, this being a cautionary procedure to demonstrate consistent equipment function. The variation in count between the two readings is rarely greater than a few percent.

Figure 3 presents the positions of the sampling stations throughout the Black Hills region. Stations 1, 3, 4, 5, 11, 12, and 13 are known as plains stations and lie in sagebrush or grassland terrain in periphery of the green area. Stations 2, 6, 7, 8, 9, and 10 are located within the Black Hills proper and constitute highly forested green area stations. The sampling routine was conducted during the middle two days of a given week. Stations 1 through 7 (constituting the southern hills circuit) were visited on Tuesday or Wednesday and the remaining stations of the northern hills circuit on the following day (Wednesday or Thursday). This two-day "back-to-back" sampling schedule was repeated every two weeks for a total of 24 sampling periods throughout the project period, May 15, 1974 to May 14, 1975.

The one significant departure from this arrangement was the single Bear Butte traverse in which an attempt was made to obtain background Aitken and near-CCN counts as a function of elevation only. This traverse was completed during the morning of May 1, 1975 at which time light to moderate winds existed with only a slight temperature inversion at low levels.

The sampling sequence was reversed every other circuit in order that a diurnal variation, if any, might be detected. The time required for obtaining all of the required meteorological and particulate concentration data for a single station varied from 10 to 30 minutes depending upon the type of weather conditions under which the measurements were made. An attempt was made to take the particle concentration measurements upwind from any known source of pollution in the nearby vicinity (such as a highway or a sawdust burner). Because the sampling area is large it is not considered necessary that all measurements for a given station be obtained at the exact same locality; i.e., in some cases one or two miles variation in the exact sampling locality was essential to avoid obvious local sources of pollution. Sampling was taken under all weather conditions (including blizzards) in order that information may be gathered on the scavenging and other modifying influences of such weather patterns on particle concentrations.

TABLE 1

Cloud Physics Laboratory Institute of Atmospheric Sciences

Field Station Report

Date: 11-13-74 Observer: D. Blair Station: S-5

A. Meteorological Observations Time: 1320

1. Wind Direction: 340 deg. 2. Wind Speed: 20-28 m.p.h.

2. Dry Bulb Temp: 34°F 4. Wet Bulb Temp: 28°F

5. Other observations (cloudiness, etc.): 60% cloud cover, clear air, cold wind, dry ground. Snow flurries in distance.

B. Condensation Nuclei Count (expansion type) Time: 1330

1. Instrument: CN-1 2. Vacuum setting a: max, max

3. Vacuum setting b: 100 4. Vacuum setting c: 10, 5

5. Count a: 4, 3 Count b: 2 7. Count c: 0.5, 0

C. Ice Nuclei Count (NCAR type) Time:

1. Instrument: 2. Operating Temp:

2. Airflow: lpm 4. Scale factor:

5. Chart reading:

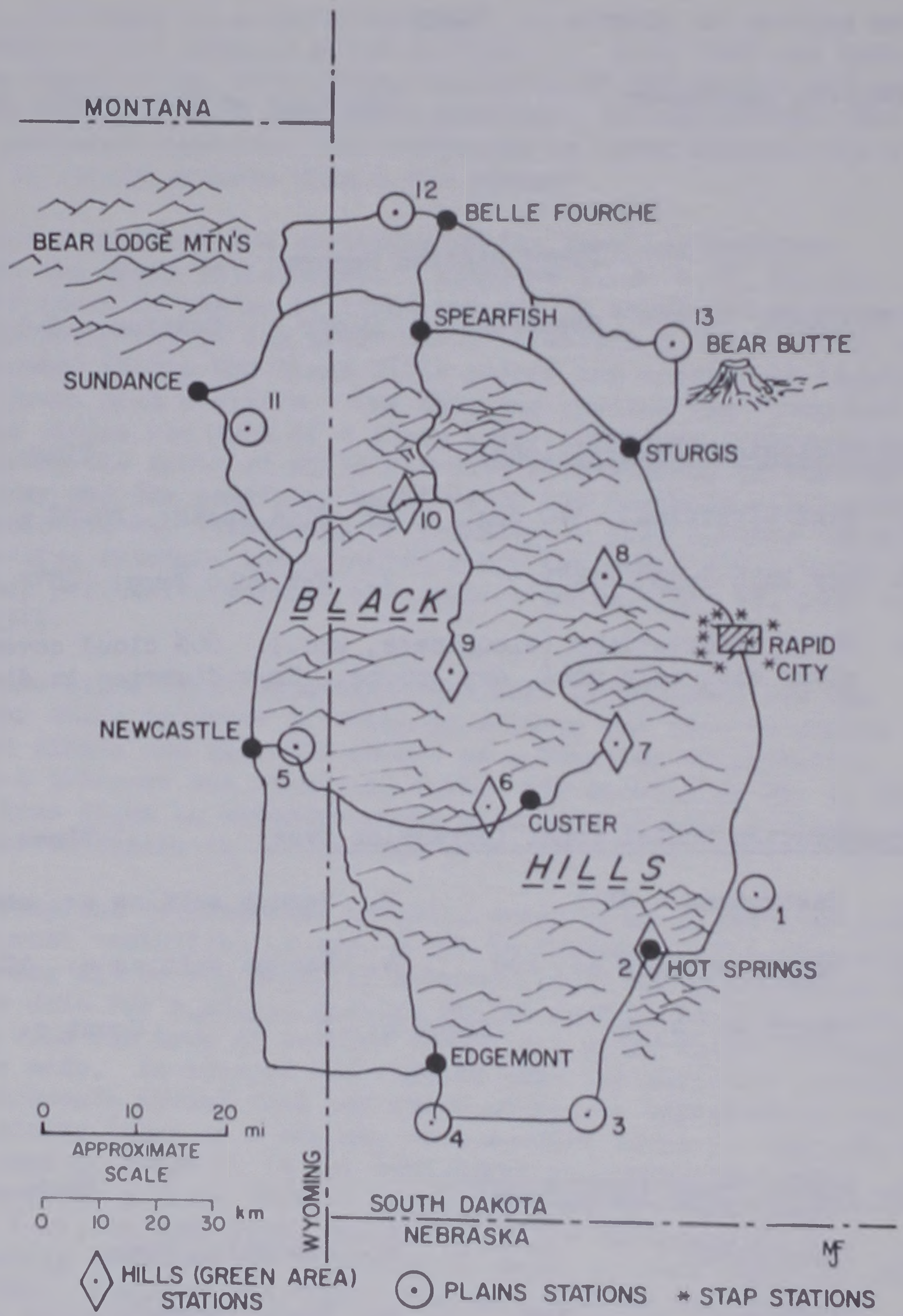

Fig. 3. SEAM sampling circuit giving locations of 13 sampling localities within and surrounding the Black Hills area. State supported sampling stations around Rapid City are indicated by *.

2.3 Analytical Methods

Standard statistical methods were applied to all data. At this stage of the study we feel that the present data base does not warrant elaborate statistical tests although a number of regression studies with pertinent correlation coefficients and standard error of estimate are included. In calculation of central tendencies of sample quantities, the geometric mean was used in preference to the arithmetic mean because of the former techniques' property of suppressing the influence of extreme values. We suspect from the data thus far collected that local source contamination has occurred from time to time resulting in such occasional extreme concentration values. In some cases smoothing techniques such as a "moving" average were used. In these examples, data within particular limiting bounds (bins) were compiled and the geometric mean of concentration determined. Either the mid-point or arithmetic mean of abscissa values within the bins was used for plotting purposes.

The geometric mean count is designated by the symbol $\hat{C}$. Thus $\hat{C}_{max}$ and $\hat{C}_{10}$ represent geometric mean Aitken and 10-torr concentrations, respectively. Average quantities are denoted by a superscript bar (e.g., $\bar{T}$ for arithmetic mean temperature).

3. RESULTS

3.1 General Observations on Particle Concentrations

The concentrations obtained at full vacuum (hereafter known as Aitken count, or "max" count) and the particulate concentrations at saturation ratios of 1.04 obtained at a 10-torr vacuum differential are shown in Fig. 4 for the sampling period May 28, 1974 through April 17, 1975. The large variability from sampling week to sampling week observed in both the Aitken and 10-torr count is now known to have resulted from differing synoptic weather conditions at the time of sampling. These variations will be related in a later section (3.5) to the scavenging effect of precipitation during various weather situations. An observable trend in the 10-torr count is a gradual lowering of the total count as the spring season approaches. The degree of data scatter also appears to be reduced during the late winter and spring months which may also be correlated with the preponderance of cool and wet days for this period.

Concentration contours have been plotted on station maps as shown in Figs. 5 and 6. There is a very striking reduction in particulate concentration level within the center of the Black Hills (for locating stations with respect to the hills terrain, compare with Fig. 3). The Rapid City data were obtained from a companion study completed under support of the State of South Dakota and includes only particulate counts from sampling days having easterly wind components in order to avoid obvious contamination from Rapid City. In spite of this precaution, the large gradient in Aitken count between the Rapid City "upwind" data and those of the surrounding stations is evident. The minimum observed in the near-CCN count of Fig. 6 at Rapid City should not be considered significant because of the limited data sample size.

It is immediately apparent that the Black Hills region constitutes a clean air reservoir; particle concentrations are almost an order of magnitude less than in the more polluted regions of the eastern slopes of the Black Hills. However, it should be remembered at this stage that this observed variation is not entirely due to the green area effect of vegetation filtration. One of the most significant aspects of the study was the direct observation of considerable scavenging of Aitken sized particles by precipitation processes. Reductions in counts due to precipitation scavenging and elevation are responsible for at least a large portion of the count variations observed in Figs. 5 and 6. The correction of the data for these factors and the utility of the data for assessment of the green area effect will be discussed in a later section.

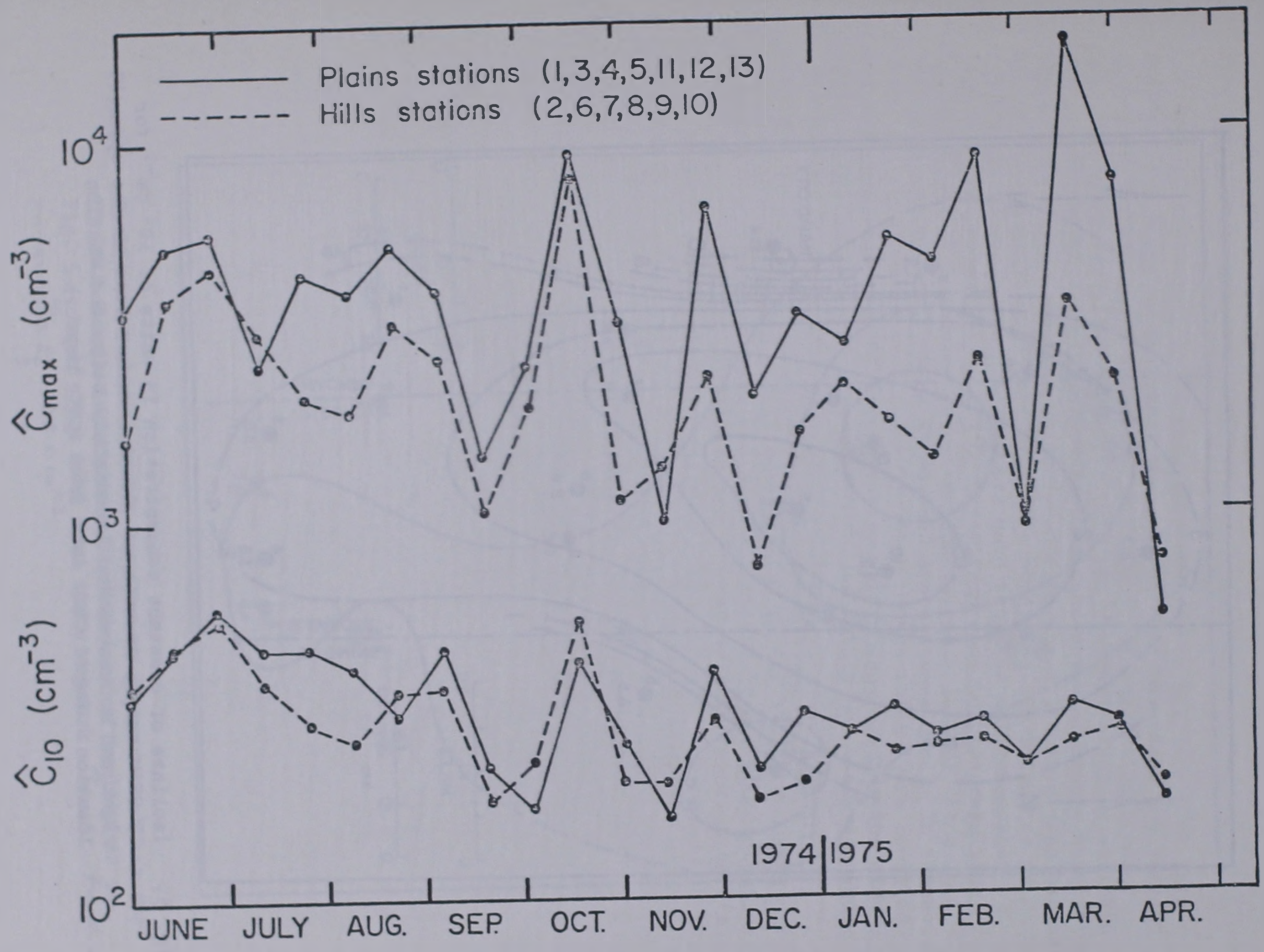

Fig. 4. Geometric mean particle concentration for Aitken (max) and 10-torr vacuum setting as a function of time during the one year sampling period. Data are stratified according to plains and hills stations.

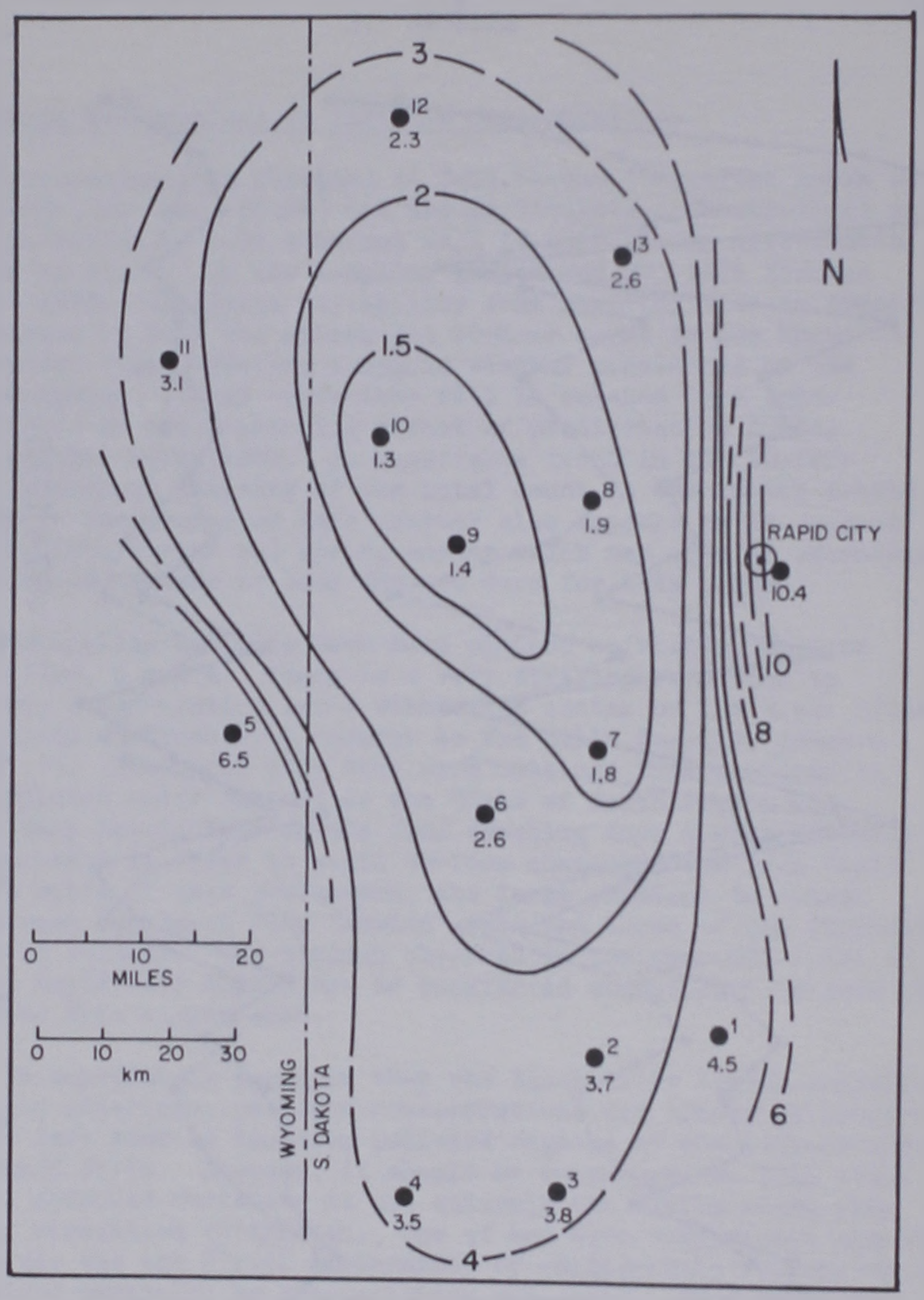

Fig. 5. Isolines of constant concentration in units of 10^3 cm^{-3} for 13 SEAM sample locations. Station number lies to the upper right and concentration immediately below the station location. Rapid City data from state network.

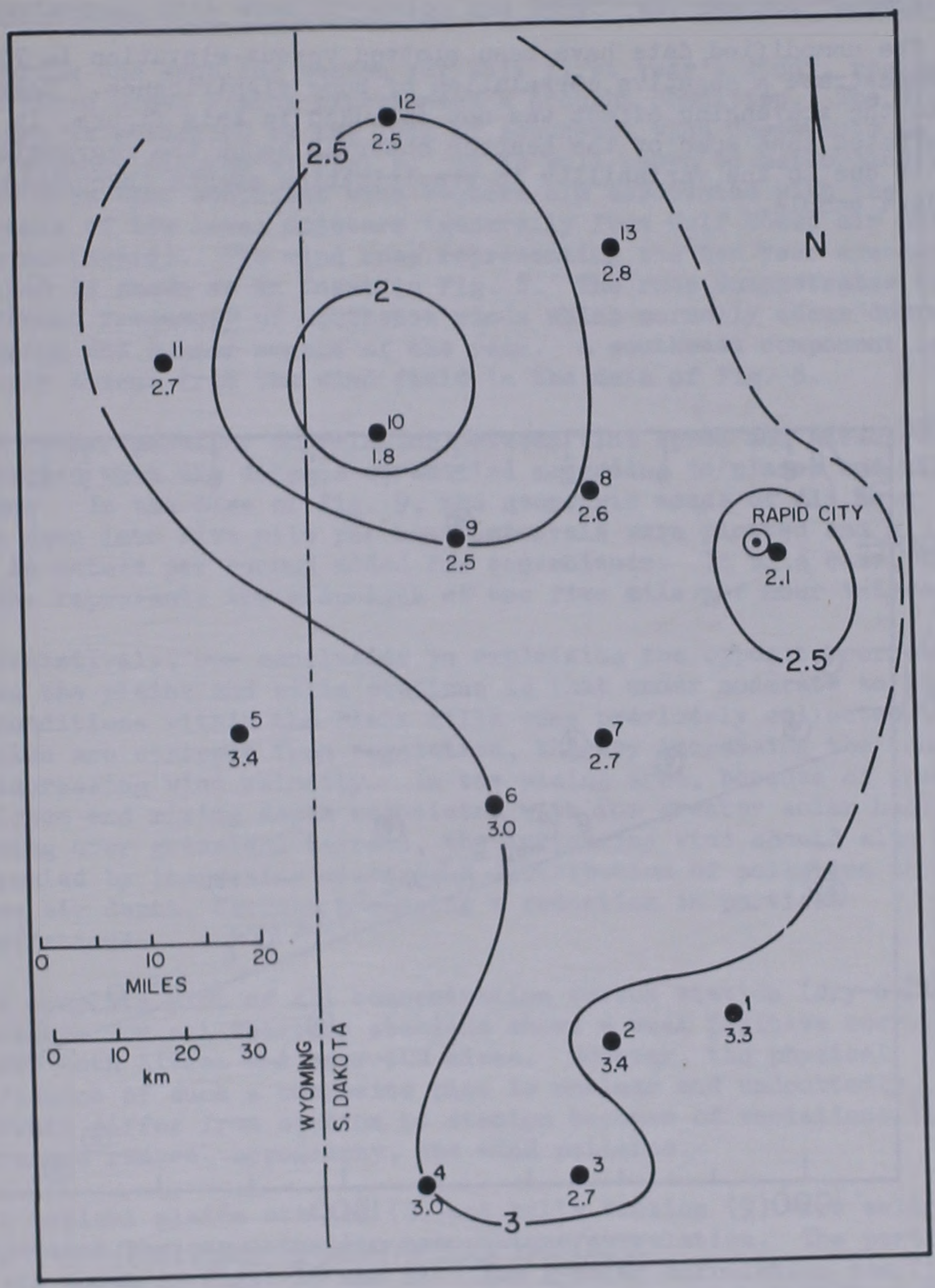

Fig. 6. Isolines of concentration for 10-torr pressure setting for 13 SEAM sample locations. Significance of numbers as in Fig. 5. Rapid City data from state network. Concentration in units of $100\ cm^{-3}$.

3.2 Variation With Elevation

The unmodified data have been plotted versus elevation in Fig. 7 to demonstrate a negative correlation of some significance. Correction due to the scavenging effect was not included in this figure; it is anticipated that some of the scatter observed about the regression line is due to the variability in precipitation events throughout the data sample.

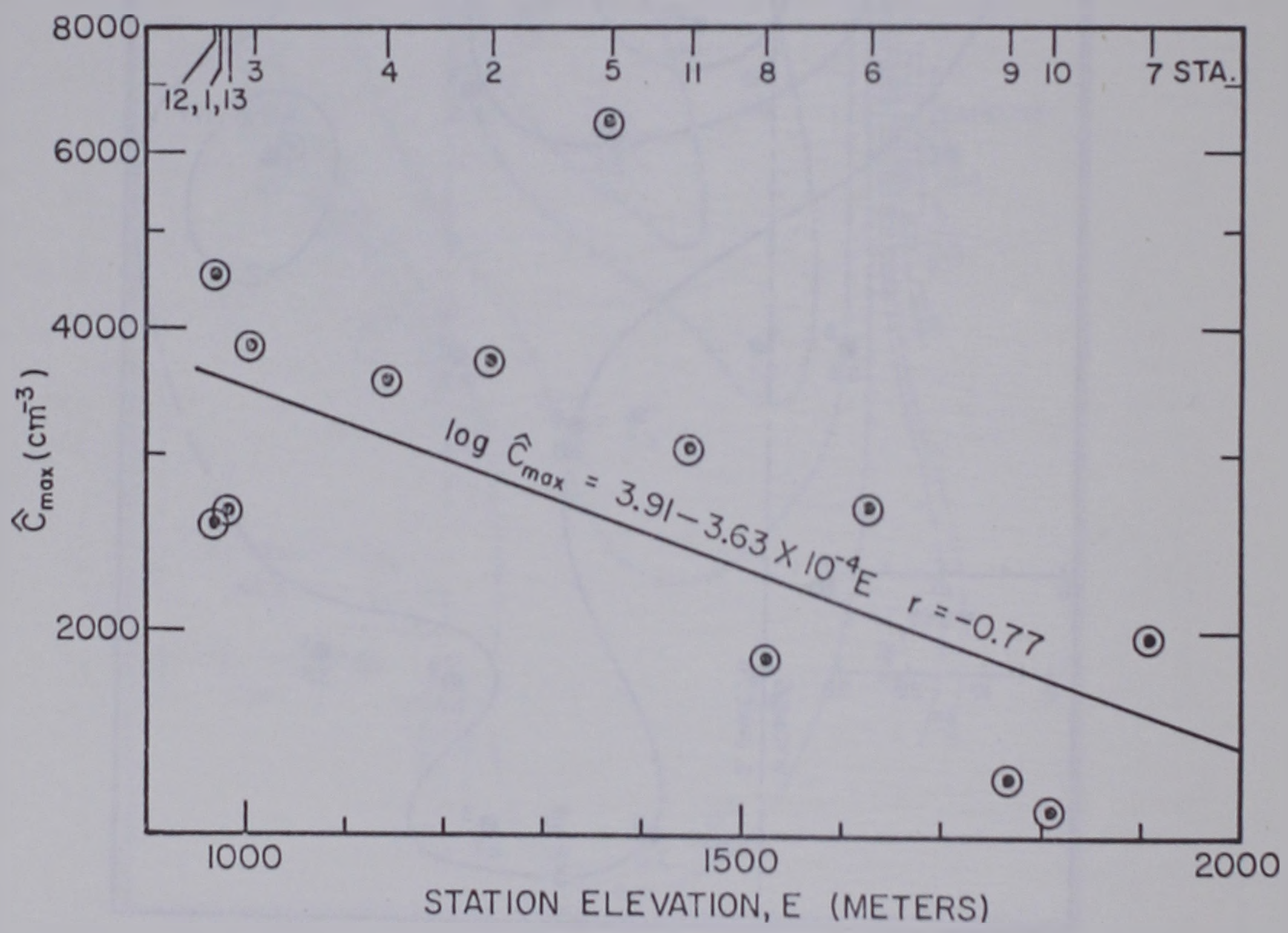

Fig. 7. Geometric mean concentration of Aitken particles as a function of station elevation. Station 5 was eliminated from the regression calculation. S_y = 0.11.

3.3 Variations With Wind Direction and Speed, and Station Temperature

During the sampling season for this first year's study, regions of the northern Great Plains experienced a drought condition. The drought condition is evidenced by the lack of southeast wind components in the wind frequency diagram of Fig. 8. It is well known to meteorologists of this area that southeast wind vectors are associated with the appearance of low level moisture (generally from Gulf Coast air masses moving northward). The wind rose representing the ten year average 1951-1960 is shown as an inset in Fig. 8. The rose demonstrates the significant frequency of southeast winds which normally occur during the spring and summer months of the year. A southeast component is obviously absent from the wind field in the data of Fig. 8.

A rather peculiar correlation between wind speed and Aitken counts is obtained when the data is stratified according to plains and hills stations. In the case of Fig. 9, the geometric means of all data broken down into five mile per hour intervals were plotted and a scale in meters per second added for convenience. In this case, the abscissa represents the midpoints of the five mile per hour intervals.

Tentatively, our conclusion in explaining the opposite correlations between the plains and hills stations is that under moderate to high wind conditions within the Black Hills some previously collected particles are stripped from vegetation, thereby increasing the count with increasing wind velocity. In the plains area, because of greater turbulence and mixing depth associated with the greater solar heating occurring over grassland terrain, the increasing wind should also be accompanied by increasing mixing and distribution of pollution to a greater air depth, thereby producing a reduction in particle concentrations.

A complete plot of all concentration versus station (dry bulb) temperature for all thirteen stations shows a weak positive correlation for both Aitken and near-CCN sizes. However, the physical significance of such a composite plot is unclear and undoubtedly the trends differ from station to station because of variations in temperature ranges, topography, and wind patterns.

A typical plains station (3) and hills station (9) were selected to represent the concentration-temperature correlation. The pertinent data are shown in Figs. 10 and 11. The greater correlation coefficient for the hills plot is most likely due to less variability in temperature and wind parameters within the forested (and somewhat sheltered) locality.

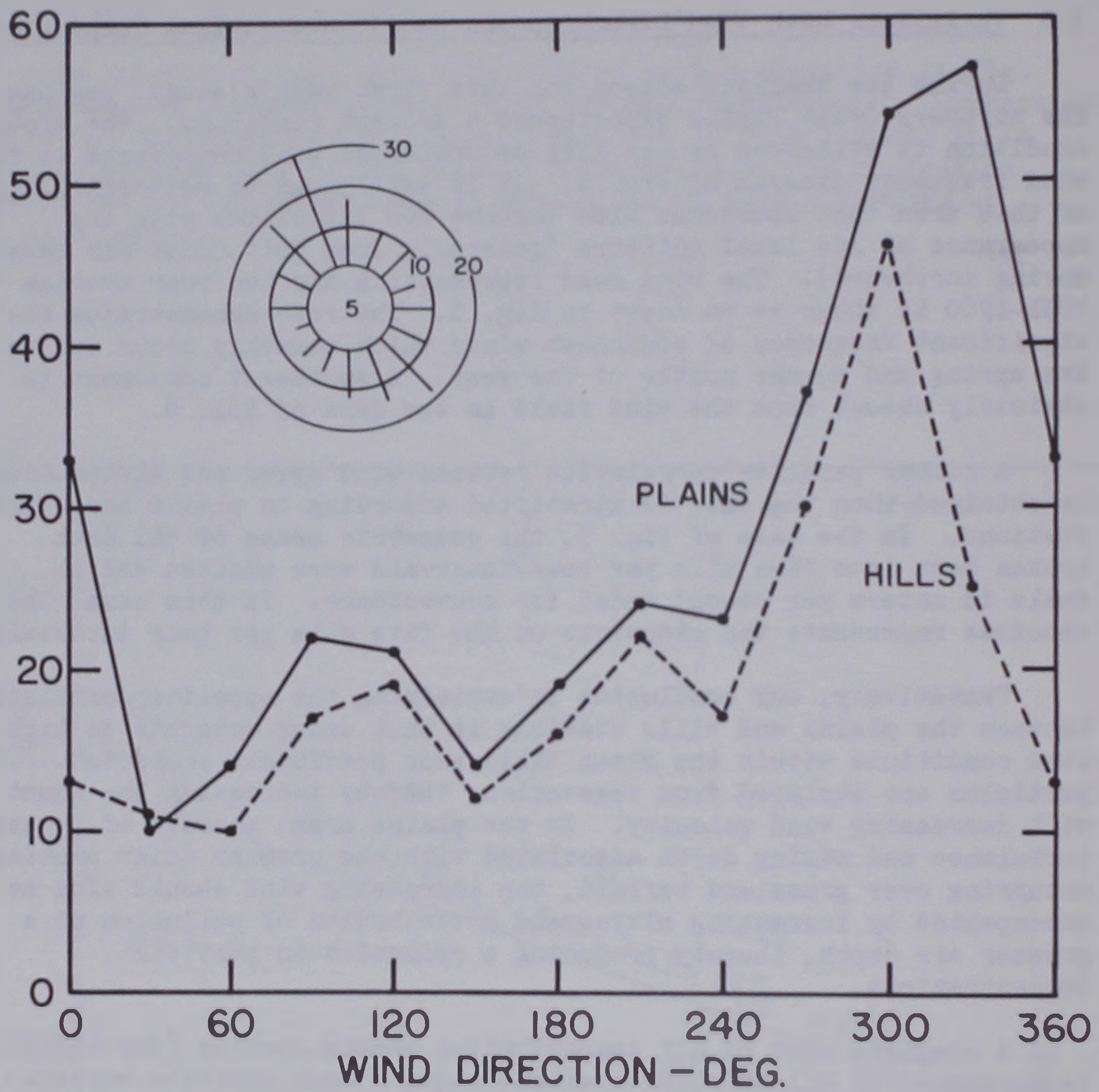

Fig. 8. Frequency of observations versus wind direction plotted according to a 60° interval, 30° moving average. Inset shows Department of Commerce wind rose data for Rapid City from 1951 to 1960. Wind frequencies are in percent of total observations with 5% of the observations indicating calm winds.

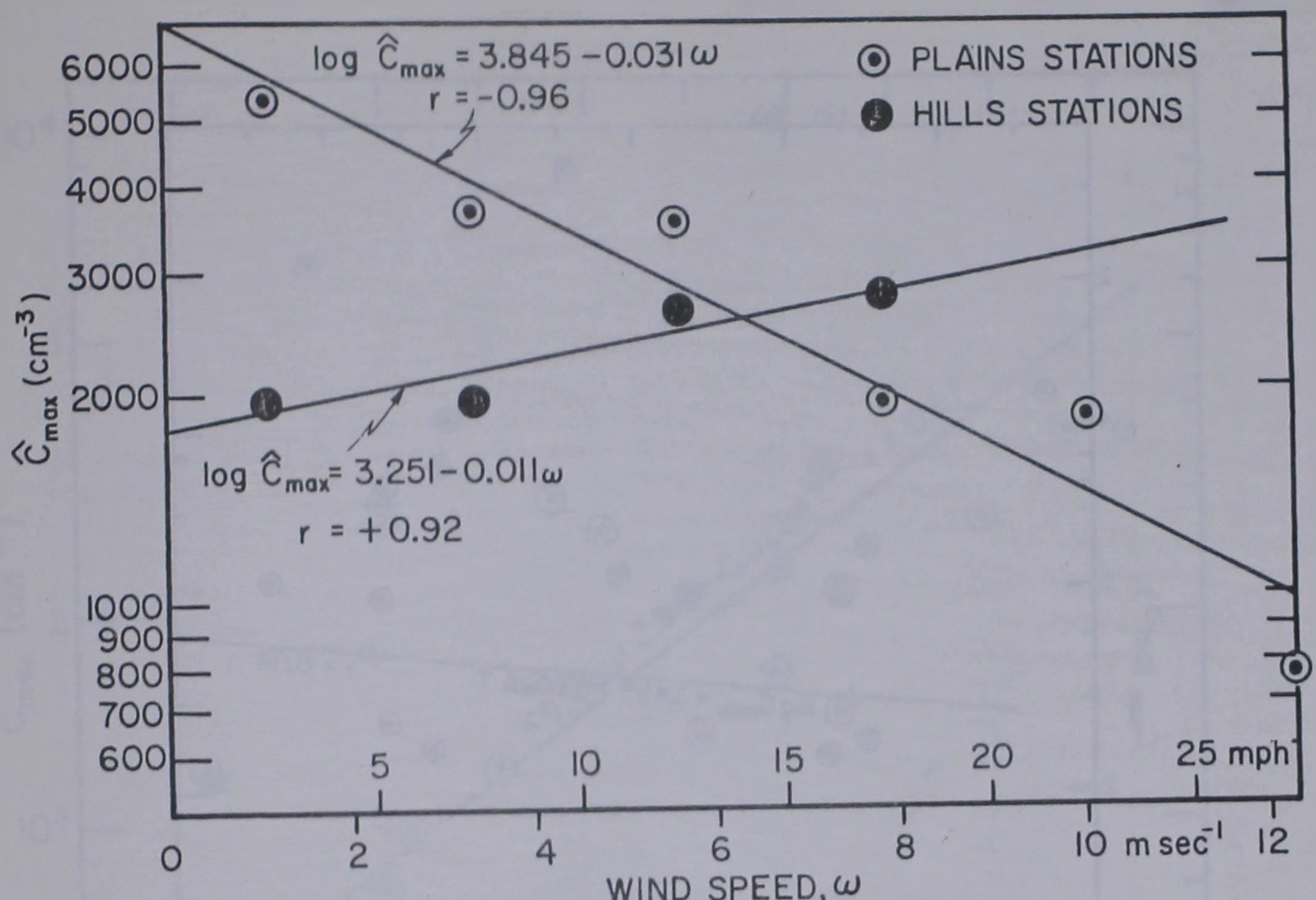

Fig. 9. Geometric mean Aitken concentration as a function of wind speed. Abscissa taken as the midpoint of 5 mph data intervals. Data stratified according to plains and hills stations. S_y(Hills) = 0.04; S_y(Plains) = 0.10.

3.4 Variation With Mixing Depth

Because of the well known increase in pollution concentration with restricted mixing depths in urban areas associated with stable air masses or basin topography, the Aitken concentrations for a small proportion of the samples were plotted against the mixing depth as obtained by inversion levels from Rapid City soundings (Fig. 12). These soundings were taken at 6 a.m. and 6 p.m. local time (MDT or MST) and were correlated with the appropriate sampling times for Stations 1 and 13. It is assumed, of course, that the inversion phenomenon recognized at Rapid City was present 60 miles north and south along the eastern slopes of the Black Hills. Because of the unlikely extension of such conditions over the Black Hills or along the western side, data from other stations were not used in this analysis. In the figure we do not observe an obvious trend of the data, and there is a suggestion of opposing trends in the distribution if the points for each station are considered separately. This, of course, would be a rather bizarre conclusion that is as yet not substantiated from the meager data base available.

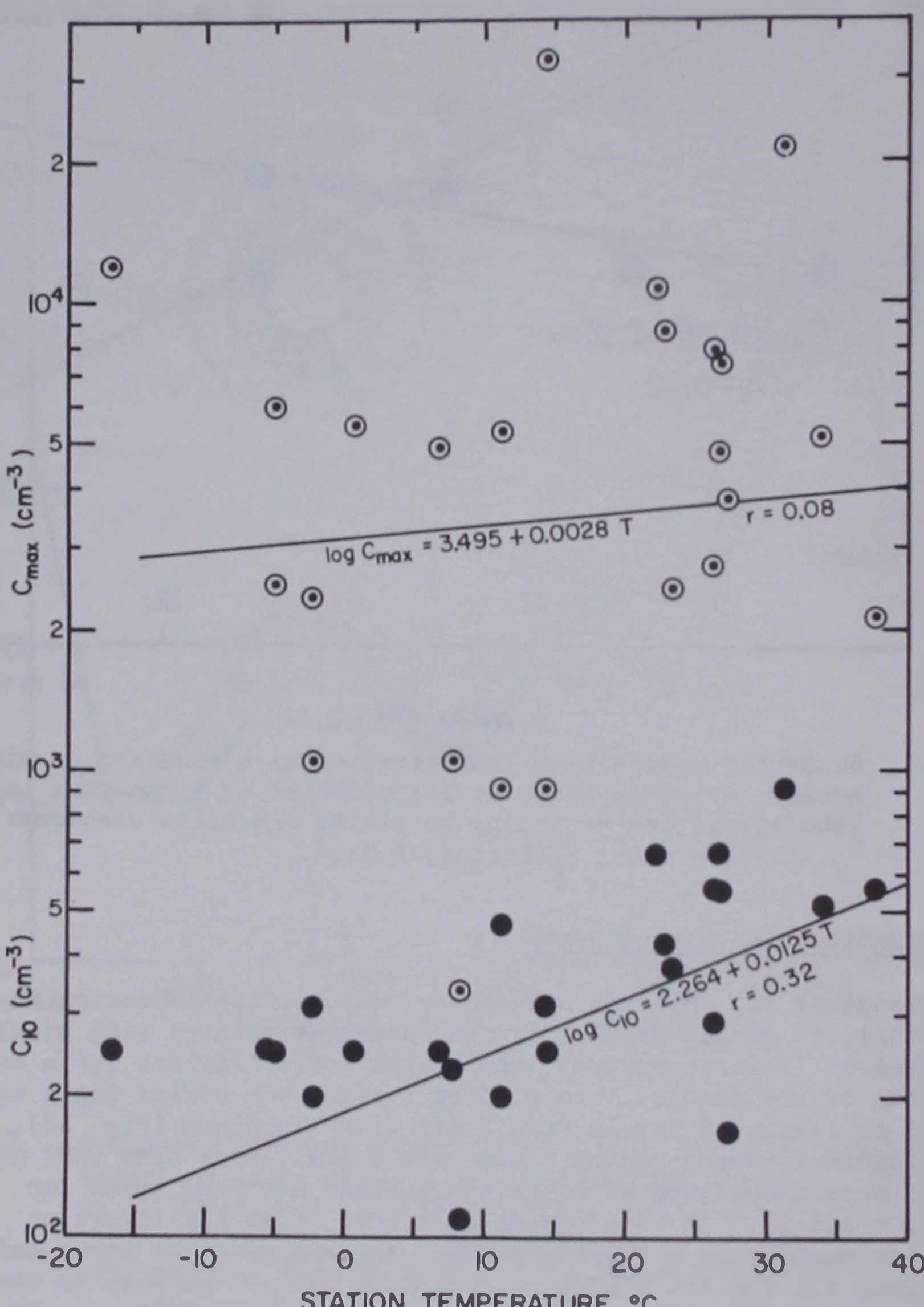

Fig. 10. Aitken and 10-torr particle concentrations versus temperature for Station 3 (near Cheyenne River). $S_y(max) = 0.47$; $S_y(10\text{-torr}) = 0.54$.

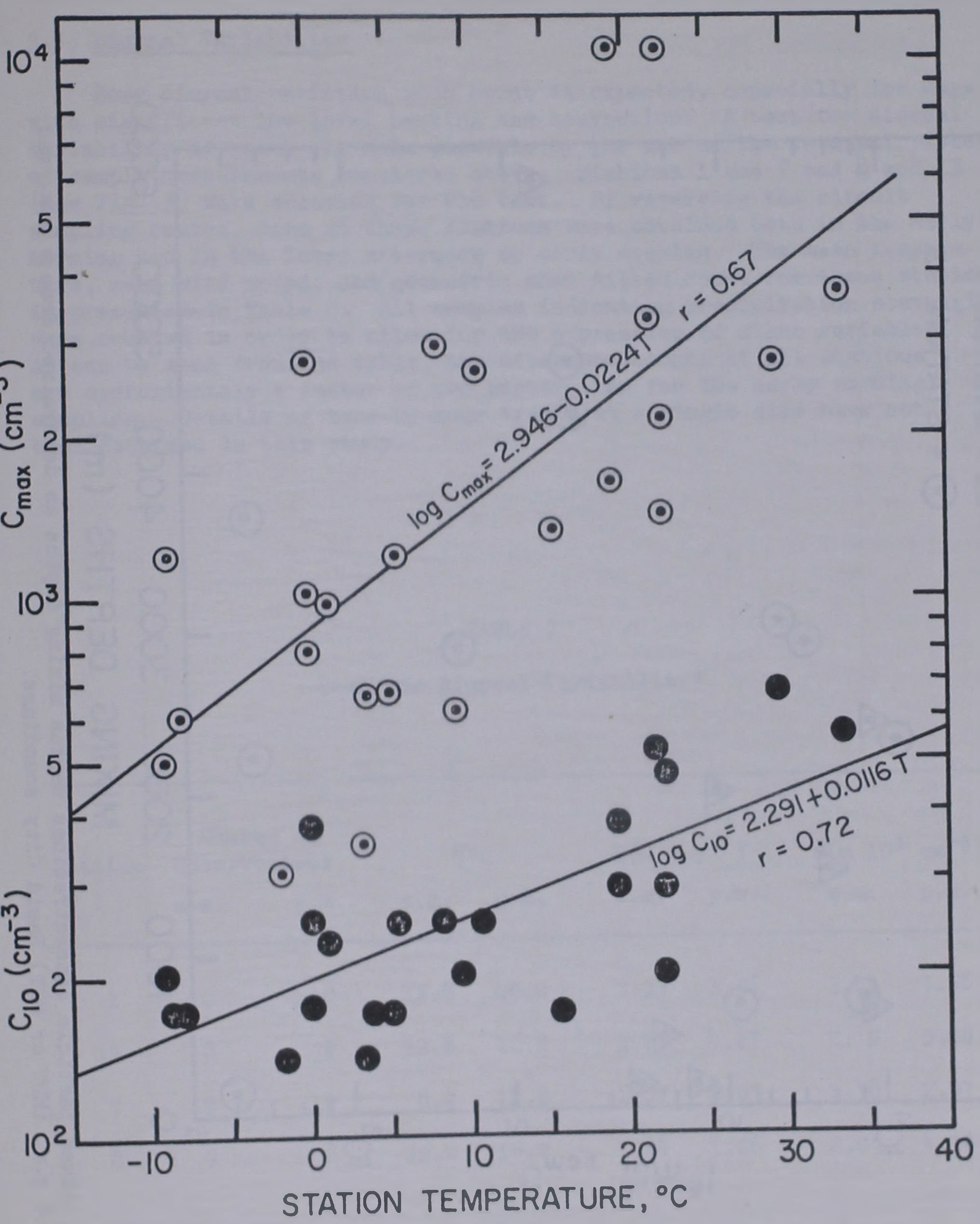

Fig. 11. Aitken and 10-torr particle concentrations versus temperature for Station 9 (near Rochford, South Dakota). $S_y(max) = 0.31$; $S_y(10\text{-torr}) = 0.14$.

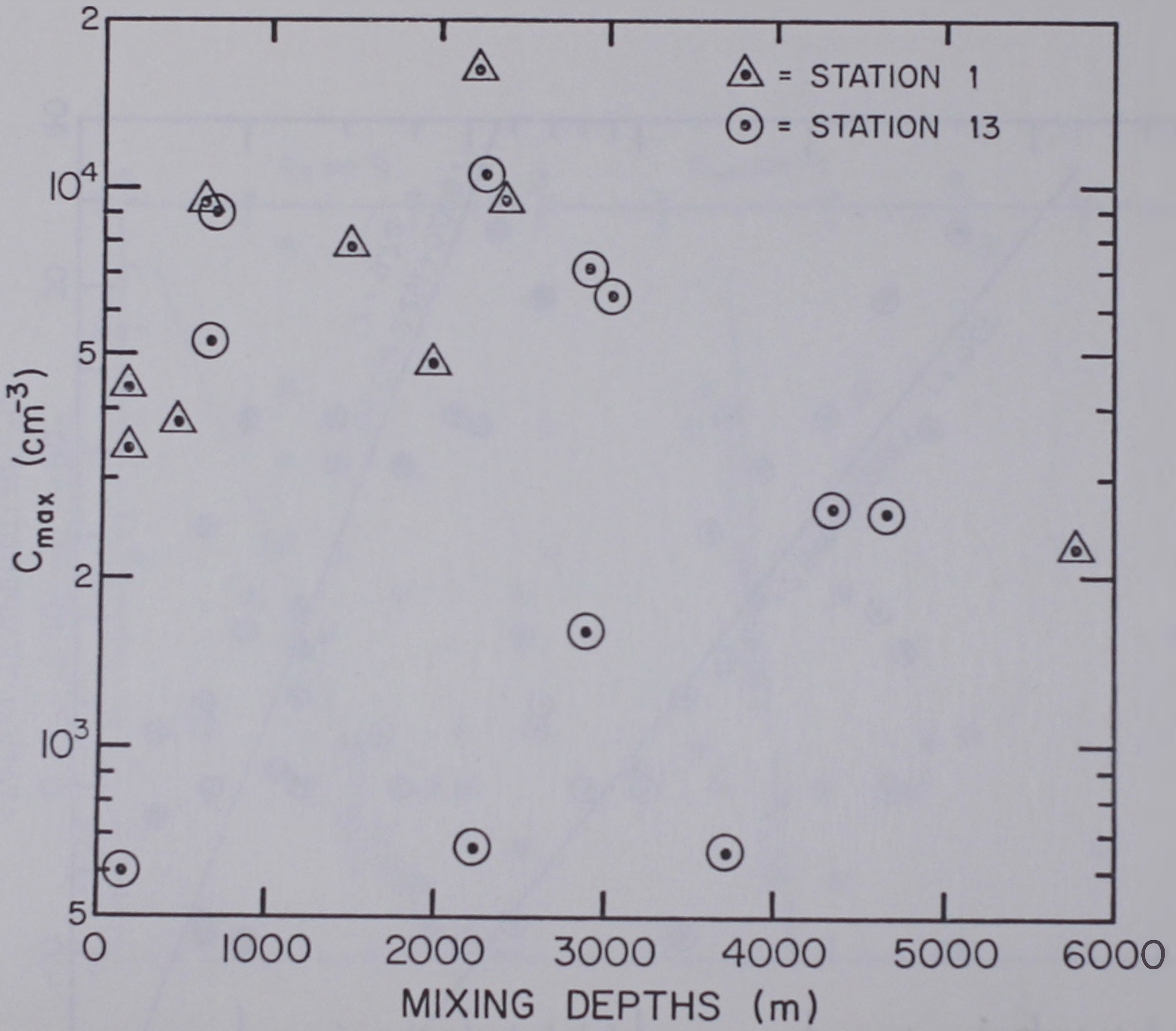

Fig. 12. Aitken particle concentrations versus mixing depths as determined from 6 a.m. and 6 p.m. (MDT or MST) Rapid City soundings.

3.5 Diurnal Variability

Some diurnal variation with count is expected, especially for days with significant low level heating and convection. A test for diurnal variability of count was made possible by the use of the reversal pattern of sample measurements mentioned above. Stations 1 and 7 and 8 and 13 (see Fig. 3) were selected for the test. By reversing the circuit sampling routes, data at these stations were obtained both in the early morning and in the later afternoon or early evening. The mean temperature, mean wind speed, and geometric mean Aitken count for these stations is presented in Table 2. All samples indicating precipitation scavenging were removed in order to allow for the expression of other variables. As can be seen from the table, the afternoon counts at all stations are approximately a factor of two higher than for the early morning sampling. Details of hour-by-hour trends at a single site have not been obtained in this study.

TABLE 2

Test for Diurnal Variability*

Station	Number of Observations		$\bar{T}$°C		$\bar{\omega}$(m sec^{-1})		$\hat{C}$(m 10^3 cm^{-3})	
	a.m.	p.m.	a.m.	p.m.	a.m.	p.m.	a.m.	p.m.
1	10	10	12.8	20.0	3.93	3.96	3.21	7.58
13	8	9	12.6	16.8	3.73	4.27	2.19	5.88
7	10	10	8.4	12.8	1.07	2.03	1.78	2.97
8	9	8	12.4	16.2	1.34	1.26	2.04	4.10

*Corrected for scavenging.

3.6 Scavenging Processes

A reexamination of Fig. 4 and the weather conditions described in the field reports leads us to the inescapable conclusion that some process is very efficient in removing aerosol particles from the atmosphere. On several occasions we have actually made pollution measurements during heavy rain or snowfall. Under these circumstances extremely low counts (as low as 200 cm^{-3} Aitken count) were observed. Though not as well documented, it was also apparent from these studies that fog at low levels was very effective in reducing the Aitken count. It is well known that high relative humidity associated with precipitation and fog create particles from the terpene vapor sources of the coniferous forest (Rasmussen, 1972), but considerable coagulation and incorporation into the fog must result in a drastic reduction in the total number of Aitken particles (whereas near-CCN or CCN count most likely remains stable or even increases).

3.6.1 Production versus scavenging; an empirical loading index

It was also observed for days where snow cover was present at or near the sampling site that abnormally high Aitken counts were exhibited. This appeared to occur at times when no apparent source of pollution could account for the abnormal measurement. The only explanation of this condition is that sublimation of the snow layer was releasing particles which were initially removed by precipitation scavenging. It is very likely that the total number of particles released was much smaller than those scavenged because of the coagulation phenomenon but that count increases become significant when the snow is subliming rather than melting. Thus we have determined three parameters which influence Aitken particle concentrations: 1) a reduction term due to precipitation scavenging, 2) a production term due to wind stripping particles from vegetation (Sec. 3.3); and 3) another production term due to snow sublimation. As a result a loading index has been devised which can be used as a predictor for small particle pollution given expected or forecast meteorological conditions.

From the regression analyses of composite hills and plains the concentrations of Aitken particles as a function of both temperature and wind velocity can be expressed as an exponential of the type

$$C(T,\omega) = e^{(a+bT+c\omega)} \qquad (1)$$

For the hills and plains data the respective equations are

$$C^H(T,\omega) = e^{(5.78 + 0.050T + 0.470\ \omega)} \qquad (2)$$

$$C^P(T,\omega) = e^{(7.08 + 0.0075T - 0.0298\omega)} \qquad (3)$$

where T is temperature in degrees Centigrade and ω is wind velocity in meters per second.

The remaining factors involved in the loading index are more qualitatively defined and subject to increased refinement with additional and more quantitative observations. Because low level cloud cover resulting from rising air parcels can also be a mechanism of air cleanup, the fractional cloud cover, C, as well as a precipitation factor, P, must be considered. The precipitation factor has been arbitrarily defined as P = 1 for no precipitation, P = 2 for light precipitation, P = 4 for moderate precipitation or low lying fog, and P = 10 for heavy precipitation.[1] We then let s be equal to the fraction of snow cover in the surrounding station area. The loading indices are then defined on the basis of these easily estimated quantities, and on the T–ω functions of Eqns. 2 and 3. Thus the loading indices are:

$$I_H = \frac{500P(1+C)}{(1+s)e^{(5.78 + 0.050T + 0.470\omega)}} \qquad (4)$$

and

$$I_P = \frac{500P(1+C)}{(1+s)e^{(7.08 + 0.0075T - 0.0298\omega)}} \qquad (5)$$

where the constant 500 is a convenient scaling factor.

Figures 13 and 14 present the geometric mean concentration for Aitken particles versus mean loading index $\overline{I}_H$ and $\overline{I}_P$ (using $\overline{s}$, $\overline{C}$, $\overline{P}$, $\overline{T}$, $\overline{\omega}$ values) for both plains and hills data respectively. The correlation is good for the hills data but somewhat less significant for

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[1] In future work we plan to use the Department of Commerce precipitation rate classification:

Light: Rate < 2.50 mm hr^{-1}
Moderate: 2.50 $\leq$ Rate < 7.50 mm hr^{-1}
Heavy: Rate $\geq$ 7.50 mm hr^{-1}

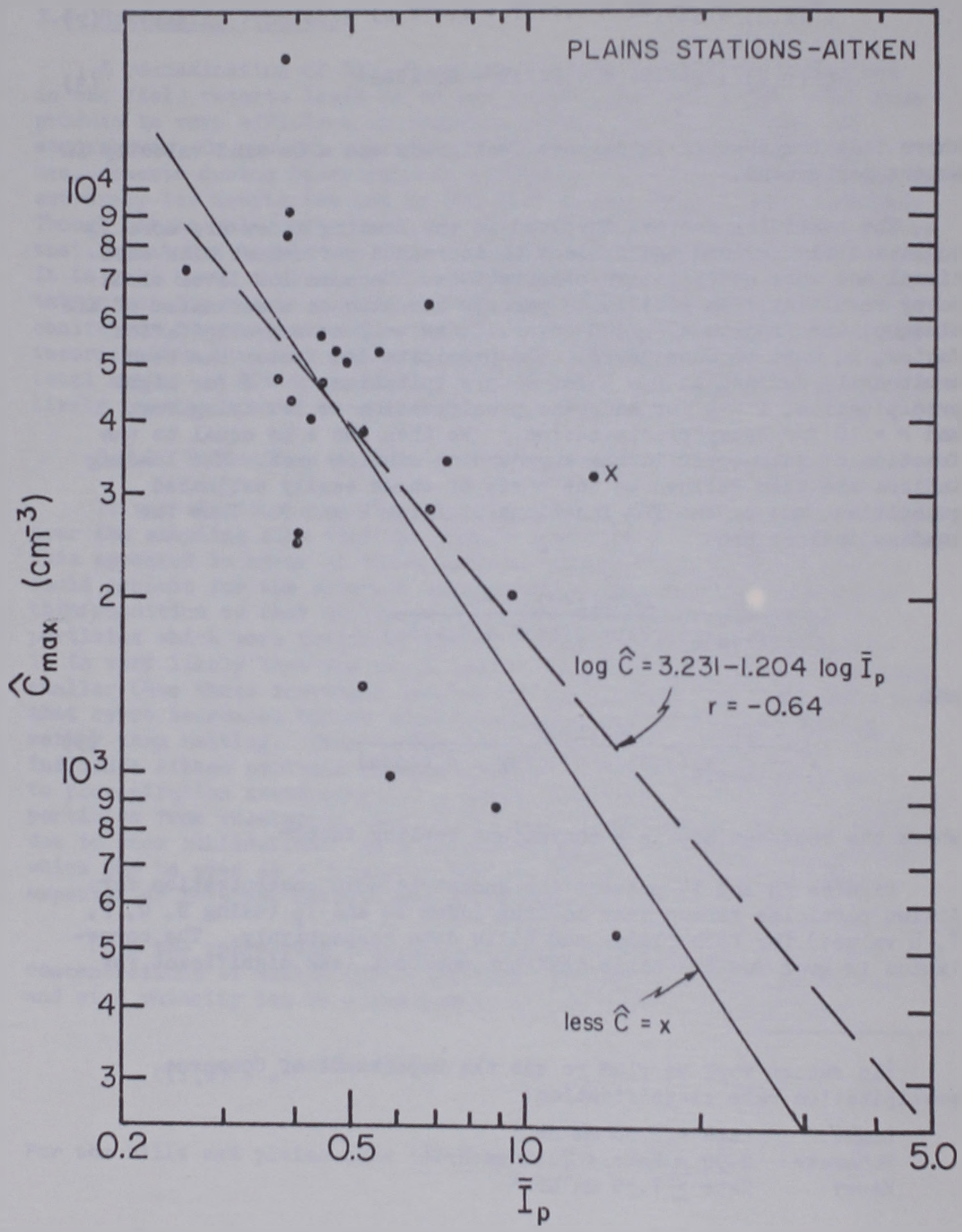

Fig. 13. Geometric mean Aitken concentration versus loading index for plains stations. See text for explanation. S_y = 0.27.

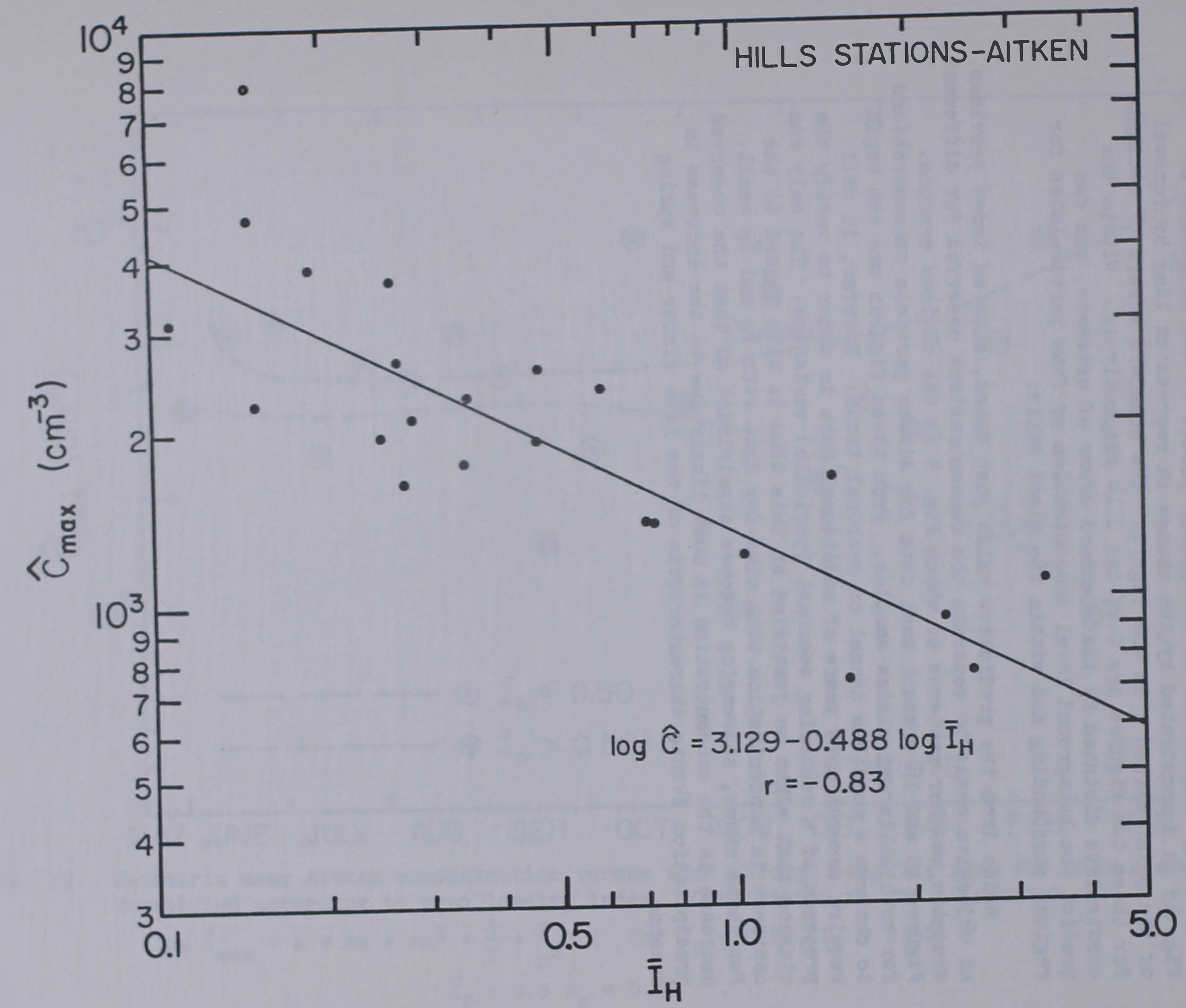

Fig. 14. Geometric mean Aitken concentration versus mean loading index for hills stations. See text for explanation. S_y = 0.14.

the plains data. The variability expected on the basis of the uncertainty in position of peripheral points in the data base of Fig. 13 is demonstrated by the change in regression line by removal of the point marked x in the figure. The standard errors of estimate for these two figures are 0.27 and 0.14 respectively. Within the constraints dictated by the standard error of estimate, one can predict the background level concentration of fine particulates for regions surrounding and within the Black Hills.

Aside from the predictive value just noted, such an index provides an objective means to separate the concentrations observed for different synoptic weather patterns of which Fig. 4 is the obvious example. Figures 15 and 16 present such data for Aitken particle concentrations for both hills and plains samples. From these figures one can begin to observe a possible annual or seasonal trend. However, it will require several more years of additional data in order to verify the presence of a recurring seasonal (periodic) variation. The only conclusion that might be justified at this time is with regard to the decrease in concentration with time for data with $\overline{I}_H$ and $\overline{I}_P$ small. For these cases, scavenging becomes significant so that the observed decrease in the concentration is most likely due to the increase in precipitation events characteristic of the late winter and spring seasons.

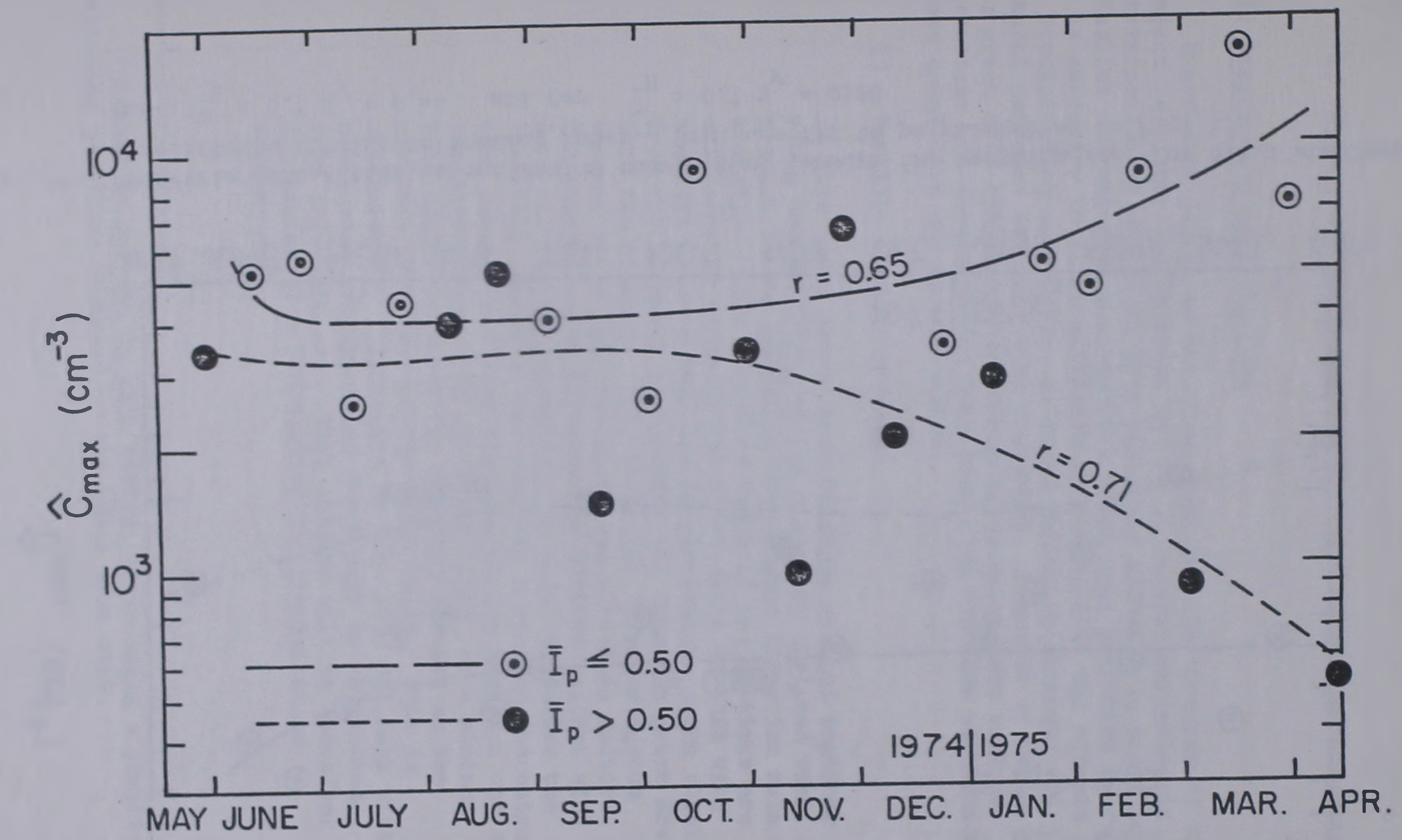

Fig. 15. Geometric mean Aitken concentration versus time through sampling year for plains stations stratified according to mean loading index. Data fitted to the polynomial

$$\log \hat{C}_{max} = a + bx + cx^2 + \frac{d}{x} + \frac{e}{x^2} \quad ; \quad \text{for } \bar{I}_p \leq 0.50,\ S_y = 0.50$$

$$\bar{I}_p > 0.5 \quad S_y = 0.67 \quad .$$

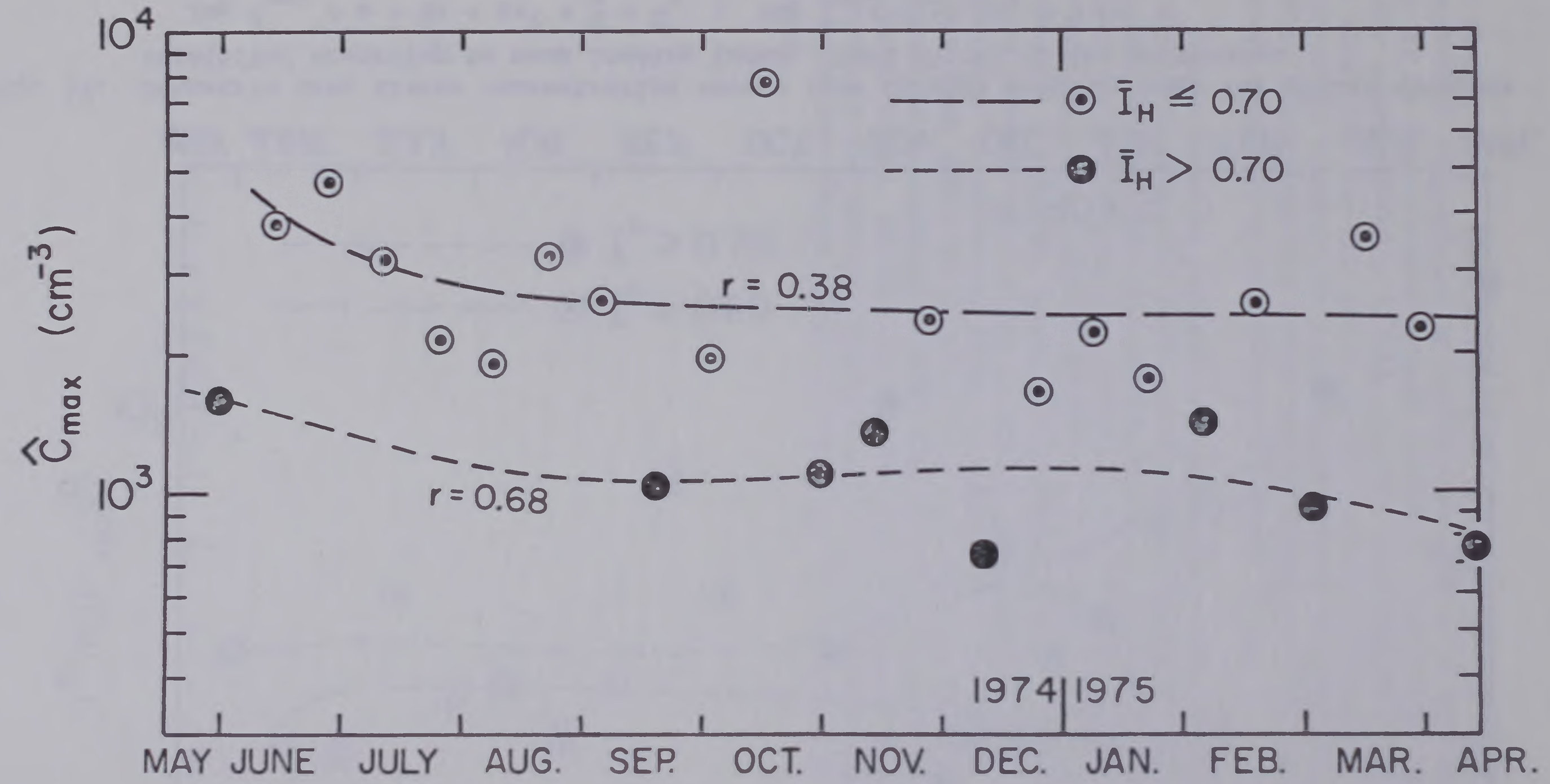

Fig. 16. Geometric mean Aitken concentration versus time through the sampling year for hills stations, stratified according to loading index. Data are fit to polynomial as in Fig. 15; for $\bar{I}_H \leq 0.7\ S_y = 0.44$ and for $\bar{I}_H > 0.7\ S_y = 0.28$.

4. DISCUSSION - ANALYSIS OF POSSIBLE GREEN AREA PROCESSES

4.1 Description of Tests Used

Experience gained in the first year sampling program of this project indicates the critical nature of several variables in determination of the green area filtering effect. In order to establish a meaningful plains/hills green area pollution profile it is necessary to first eliminate or standardize the effects of 1) precipitation scavenging, 2) local pollution sources; and 3) natural decrease in count with elevation. A number of tests for the green area effect are described below which have various advantages and disadvantages that stem from the ease with which these quantities may be controlled.

1) Particle Shadow Approach[2]

In this test, one or more stations grouped together along the periphery of the hills are analyzed with respect to the pollution versus wind direction relationship. This method is valid if the stations are sufficiently close to the Black Hills so that with moderate winds a decrease in particulate count results from the movement of filtered air from the green area onto the station. This technique is advantageous because it is independent of the elevation factor. The concentration parameter is plotted against wind from all compass directions in order to define the "particle shadow". For example, a minimum concentration should occur for stations at the southern end of the Black Hills with northerly winds, or a minimum with southerly winds for stations located at the northern periphery of the Black Hills. This is schematically illustrated in Fig. 17. All days with a recorded precipitation event must be eliminated from this data set. This process will be hereafter designated as a "correction for precipitation scavenging".

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[2]Similar in concept to rain shadow, there being a paucity of pollution particles downwind of the green area sink.

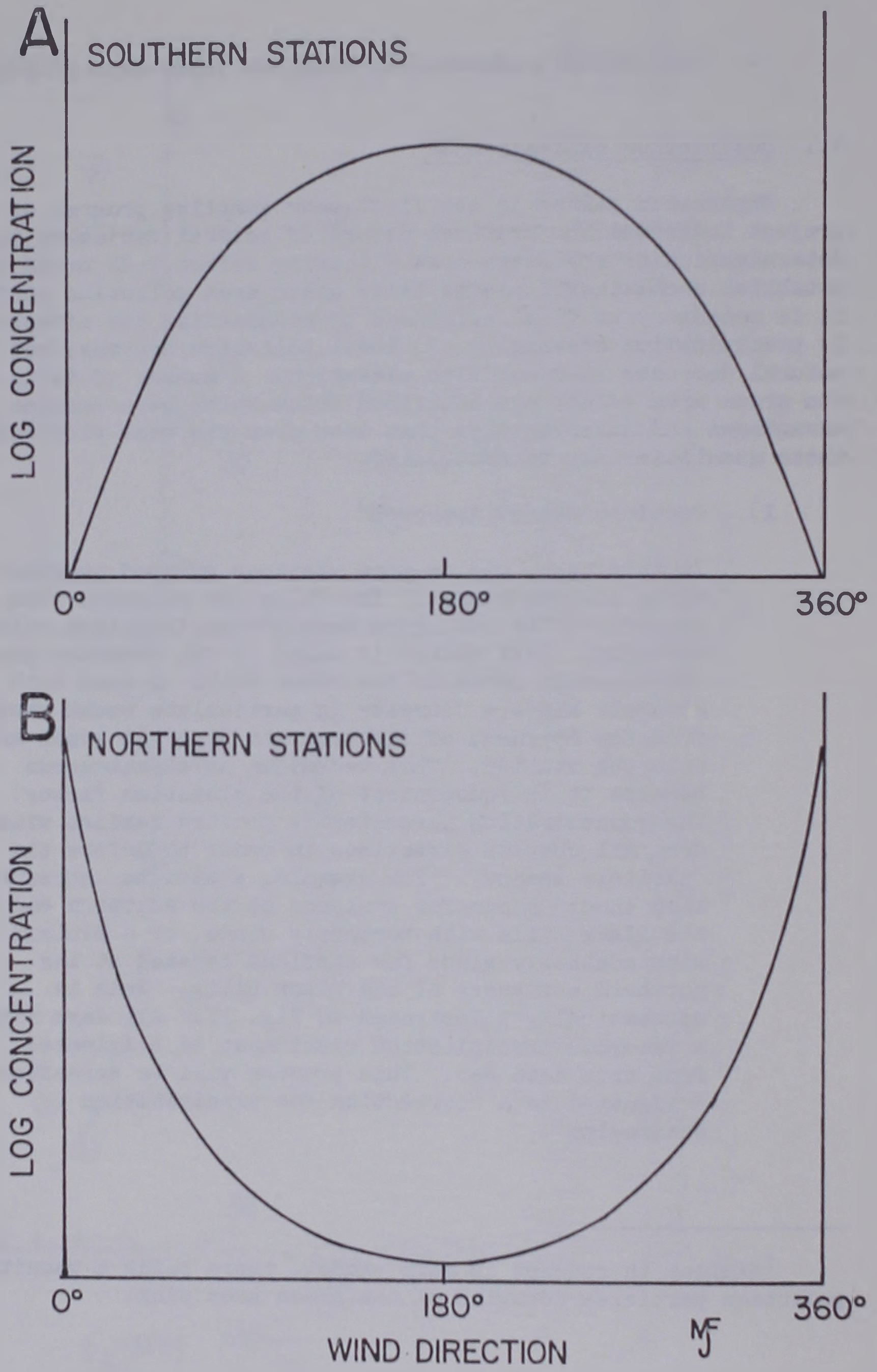

Fig. 17. Hypothetical distribution of concentration versus wind direction for southern and northern plains stations for the particle shadow test.

2. The Equi-Elevation Test

The elevation variable can be eliminated by selection of two stations with identical elevation -- one in the green area and one outside the green area. This is essentially the system used in the Cincinnati and Hyde Park analysis. In these cases appropriate wind sectors must be chosen to eliminate local sources of pollution and scavenging by precipitation must also be eliminated as in (1).

3. Elevation-Correction Method

In this technique a direct determination of the background elevation change of pollution is required and can best be obtained by single station measurements from a tower, from a balloon, or less ideally, from a relatively high topographical feature. It is important that the weather conditions that existed at the time of a vertical profile measurement also be similar to those of the composite data used in the analysis. As an example, precipitation scavenging must be eliminated unless nearly identical precipitation processes occurred in the two sets of measurements. Data obtained for periods of precipitation should be avoided in any case because of the greatly reduced level of counts observed.

4. Opposing Wind-Sector (Single Station) Test

This test is similar to Method 1 except that only selected wind sectors are used rather than a plotting of concentration versus wind direction throughout the compass. In this case, care must be exercised to avoid inclusion of local pollution sources lying within the wind sector. This also has the advantage of eliminating the elevation variable.

5. Traverse "Two-Counter" Method

In this method simultaneous measurements are made for the elevation data over the traverse from the plains sector into the green area, covering the same elevations and as nearly as possible the same weather conditions. In the present study the two-counter method has not been used, but future work will include attempts to make such measurements.

4.2 Results of Analysis

Attempts have been made using all of Tests 1 - 4 to assess the green area effect on Aitken particle reduction. Figures 18 and 19 present the results of the particle shadow test for Stations 1, 3, and 4 in the southern hills and Stations 11, 12, and 13 in the northern hills. A similar pattern is observed in a smoothed "moving" average profile of the individual Stations 3 and 13 at the southwestern and northeastern extremities of the study area, as shown in Fig. 20. It is obvious in all cases (although more strikingly so in Fig. 19 for the composite northern plains stations) that a source of particulates from the southwest dominates the data. In comparison with Fig. 17, we see that a minimum in count should exist from northerly winds for the southern hills stations. In a crude manner this appears to be true for the data of Fig. 18. However, the reversal with low count at 180° is not observed in Fig. 19, but a strong opposite trend is apparent. Only two explanations for this contradiction are possible at this time. The most logical explanation is that sufficient pollution is coming from the northern hills towns of Sturgis, Whitewood, Spearfish, and Lead - Deadwood (to the south of Stations 11, 12, and 13) that the green area effect has been masked by these local sources. Unfortunately, if the appropriate wind sectors were removed from the direction span of Fig. 19 to eliminate these sources of pollution, there would not be any remaining portion of the compass points from which data could be obtained. We prefer to accept the first explanation because of the strong reverse correlation observed in Fig. 19 for the northern hills stations. One would expect the southern hills stations to show the stronger relationship if a large scale (regional) source were to lie to the south-southwest.

A few stations in the Rapid City area, utilizing data from the state project, were used for the equi-elevation test. Table 3 presents these data and indicates a significant green area cleanup for the eastern Black Hills area. Note that the wind sectors were selected to avoid contamination from the Rapid City plume itself. Inasmuch as these data represent the geometric means of a large number (>80) of samples, some weight should be given to the conclusions of this study in the overall green area evaluation.[3]

Figure 21 presents the Bear Butte traverse data used for the elevation-correction test. Because of the uncertainty in the strength of the gradient below 1100 meters, only the trend from 1100 meters and

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[3]A complete report of the Rapid City study is now in preparation.

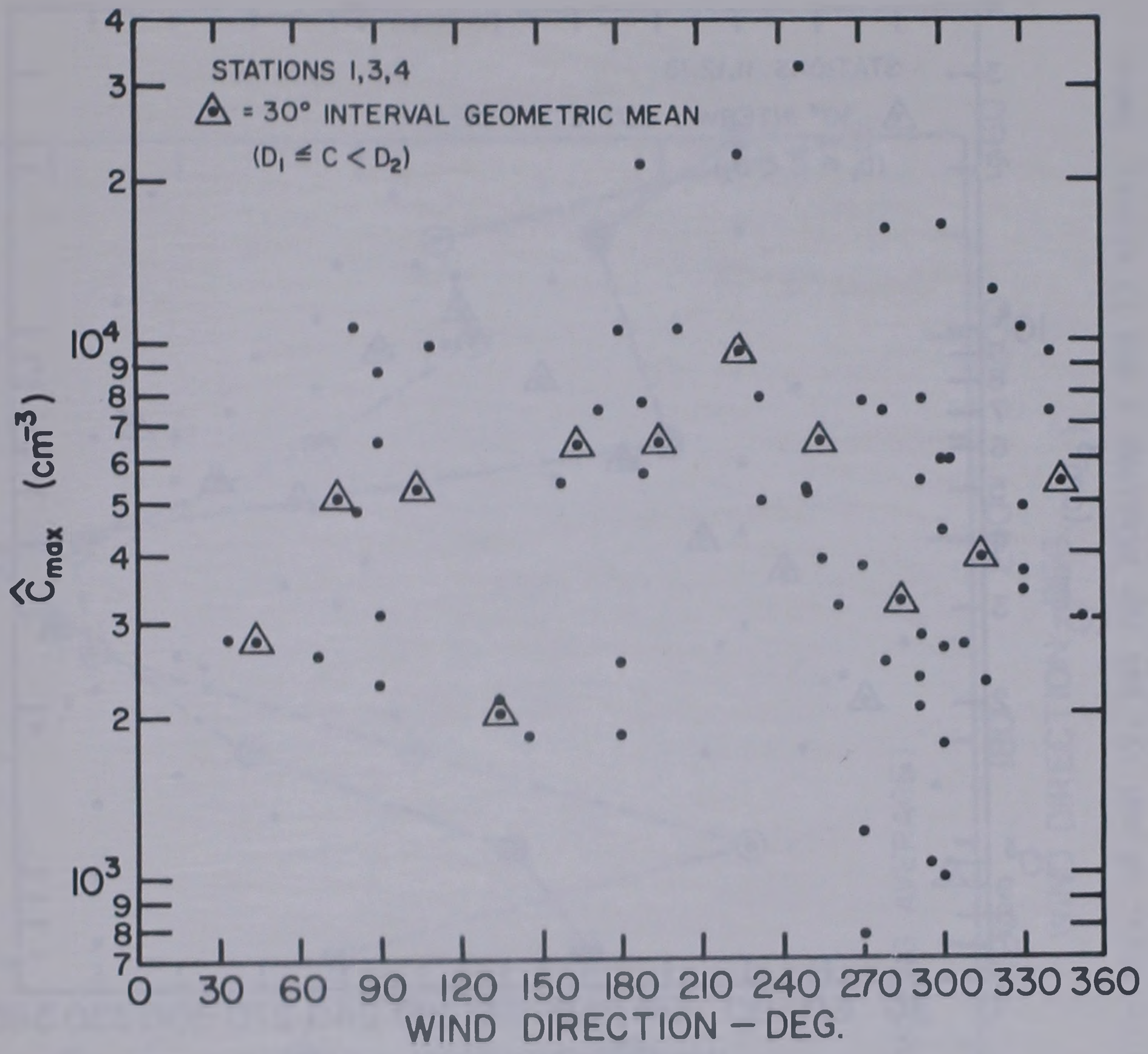

Fig. 18. Geometric mean Aitken concentration versus wind direction for the particle shadow test for Stations 1, 3, and 4. Data corrected for precipitation scavenging.

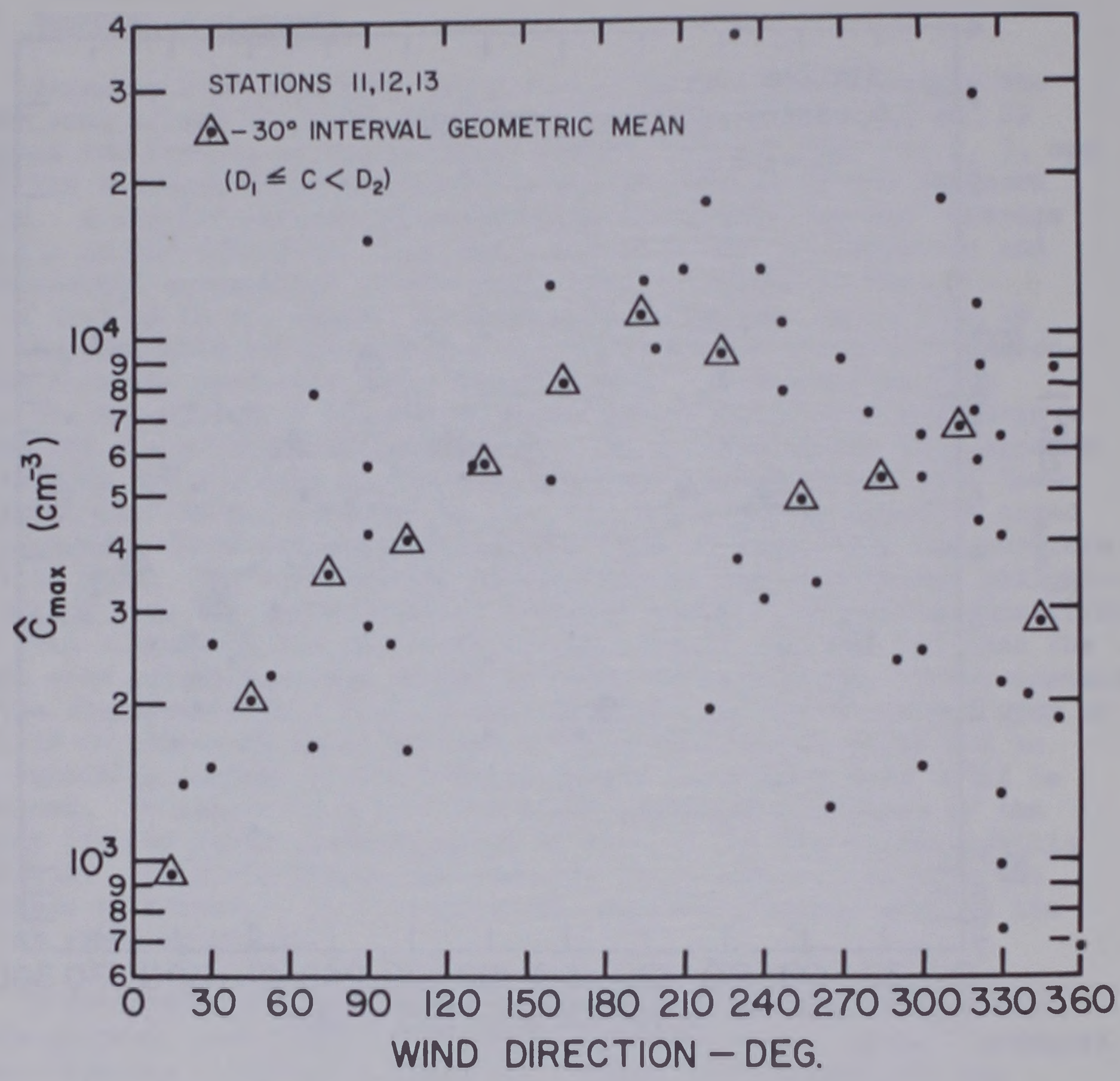

Fig. 19. Geometric mean Aitken concentration versus wind direction for particle shadow test for Stations 11, 12, and 13. Data are corrected for precipitation scavenging.

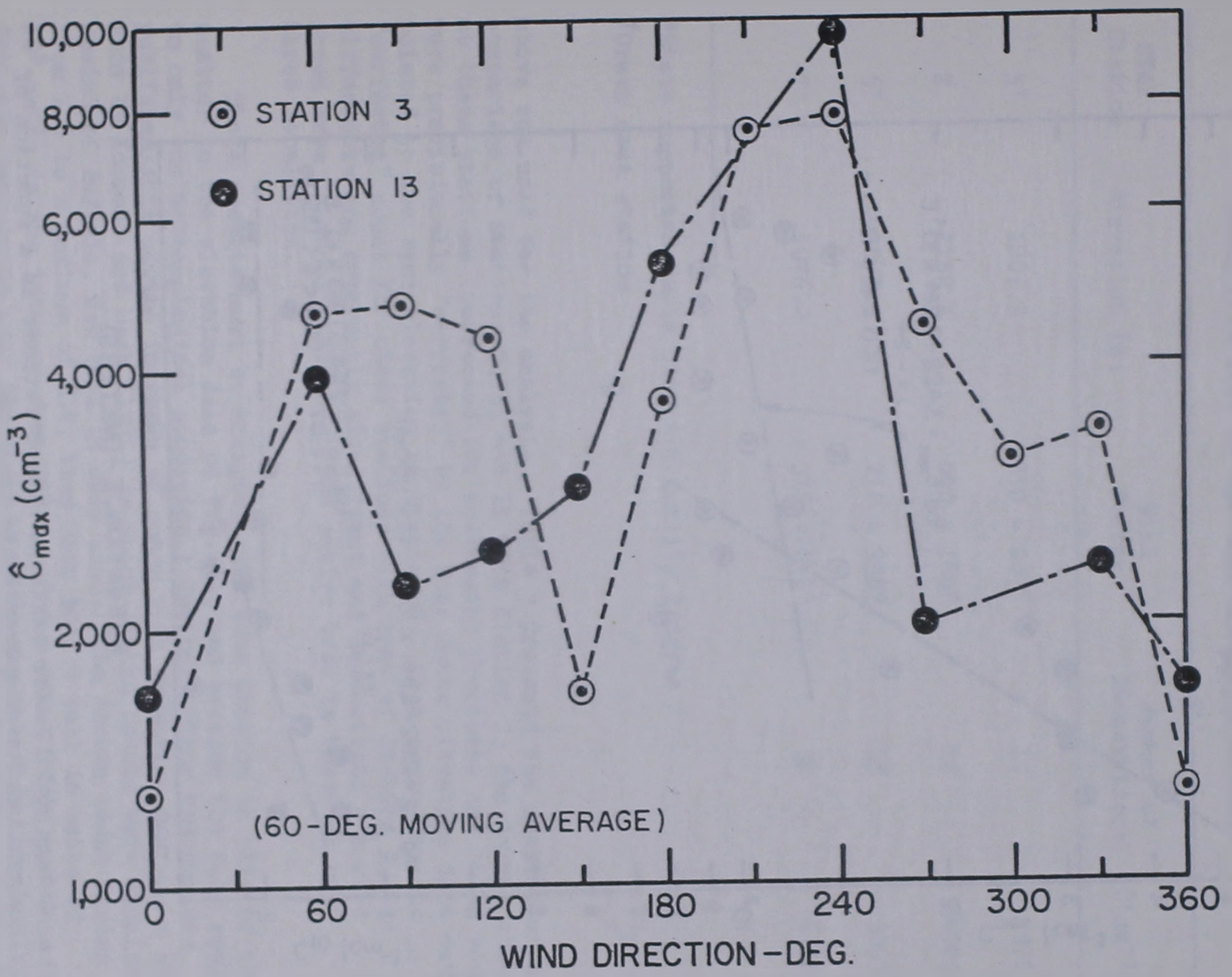

Fig. 20. Particle shadow tests as in Figs. 18 and 19, but for Stations 3 and 13 alone. Data are corrected for precipitation scavenging.

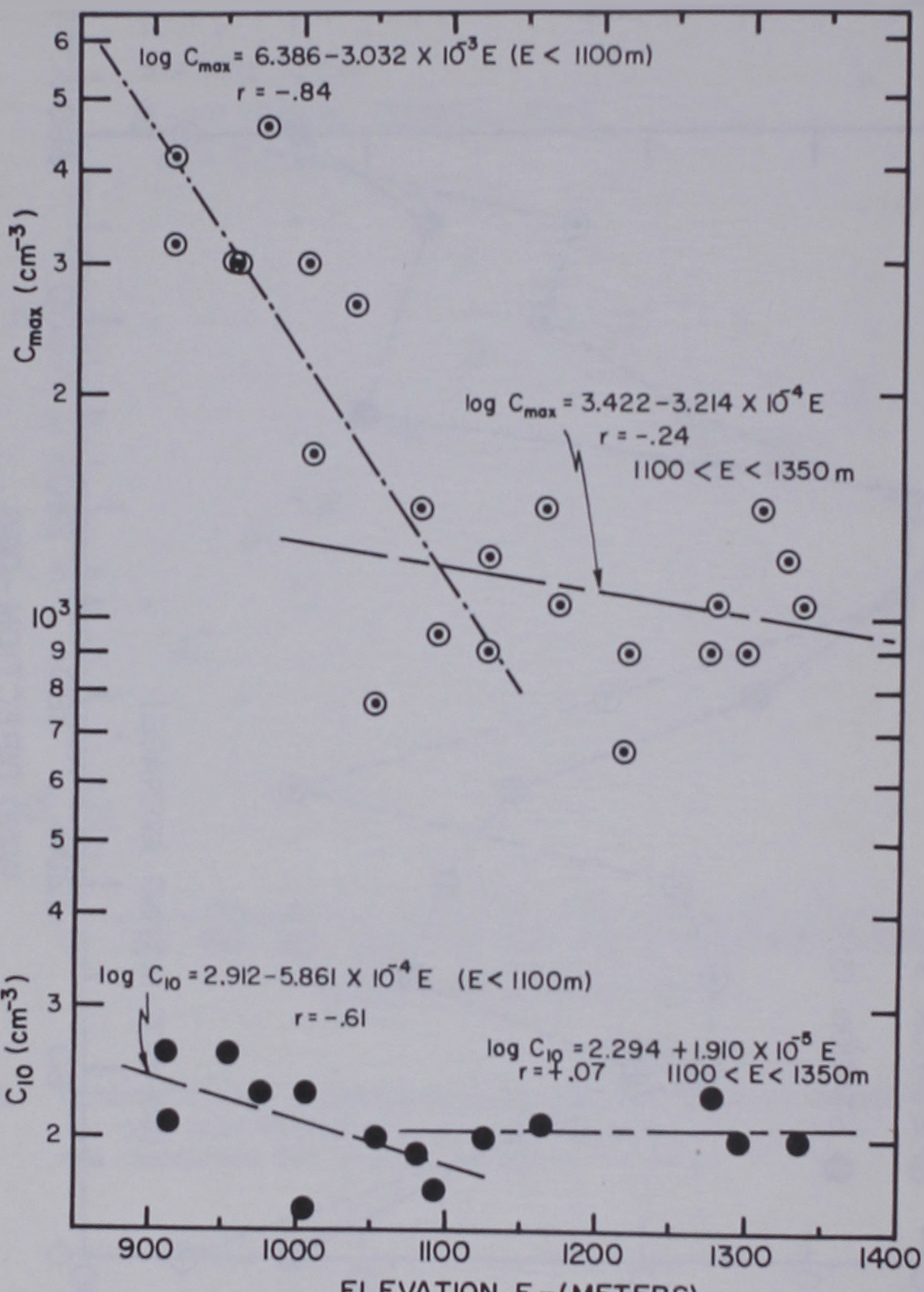

Fig. 21. Aitken and 10-torr particle concentrations as a function of elevation for the Bear Butte traverse. S_y(max;E<1100) = 0.15; S_y(max;E>1100)=0.14; S_y(10-torr);E<1100)=0.06; S_y(10-torr); E>1100)=0.03.

TABLE 3

Green Area Test by the Equi-Elevation Method*

STAP Station	Elevation (m)	Wind Sector	Number of Observations	$\hat{C}(cm^{-3})$
5†	1207.3	250 - 007°	15	2376
2	1152.4	090 - 180°	19	84920
6†	1079.3	210 - 330°	35	3025
7	1076.2	315 - 045°	32	6116

*State supported Rapid City Air Quality Program

†Green area station

above was used for the analysis. Table 4 presents the results of a comparison of Stations 4, 5, and 11 with Station 9; the counts observed at these stations (corrected for scavenging processes and local sources) were provisionally "corrected" by the Bear Butte elevation data extrapolated to the same elevation as Station 9. When comparing the "corrected" count for these stations with that of Station 9, the differences are apparently significant and demonstrate a marked green area "cleanup", although the entire test is based on only three localities.

These results must be accepted with some caution in view of the scatter in the elevation data of Fig. 21, and because the data apply to only one meteorological condition. The only other appropriate published data on the increase of count with elevation is from a study made by Kocmond and Mack (1972) in which Aitken counts were obtained upwind of Buffalo, New York in July 1969. The Aitken count varied from 1.6 to a maximum of 2.4, then down to 1.3 (all in units of 10^3 cm^{-3}) in the interval from 915 to 1830 m MSL. It is probable that the turbulence over the Buffalo plume may have been responsible for the slight rise in count at 1220 m. In this case, the gradient of Aitken count is similar to that on Bear Butte for E > 1100 m.

TABLE 4

Green Area Effect from Elevation-Correction Data

Station	Number of Observations	Actual Count*	Elevation	Corrected Count
9†	18	1,904 cm^{-3}	1768 cm	1,904 cm^{-3}
4	5	3,402 cm^{-3}	1142 m	2,048 cm^{-3}
5	12	7,939 cm^{-3}	1372 m	5,939 cm^{-3}
11	12	5,570 cm^{-3}	1458 m	4,470 cm^{-3}

*Corrected for scavenging processes and local sources.

†Green area station.

We can conclude from the elevation-correction test that some green area effect may be observable, although the exact magnitude is uncertain due to the lack of a sufficiently reliable elevation trend.

Perhaps the most convincing test has been the opposing wind sector test illustrated by the data of Fig. 22. Care was taken to restrict the wind sectors so that local sources of pollution are avoided. These sources of pollution are indicated by the filled triangles of Fig. 22. In these cases, then, we are comparing the concentration level within air flowing out of a restricted portion of the green area and over the station to that of air moving toward the station from the plains area. Data from the eastern side of the Black Hills were not included because of the shielding effect of pollution sources in this area (which affected our particle-shadow test). In all cases there is a decrease in count from the hills area sector to the plains sector. In the case of Station 12, the green area is composed of the Bear Lodge Mountains rather than the Black Hills. It will be noted that pollution sources exist 20 or 30 miles away from the wind sector in the case of Station 12. These distances are believed to be sufficiently large as to preclude overriding of the green area effect by the local sources of pollution.

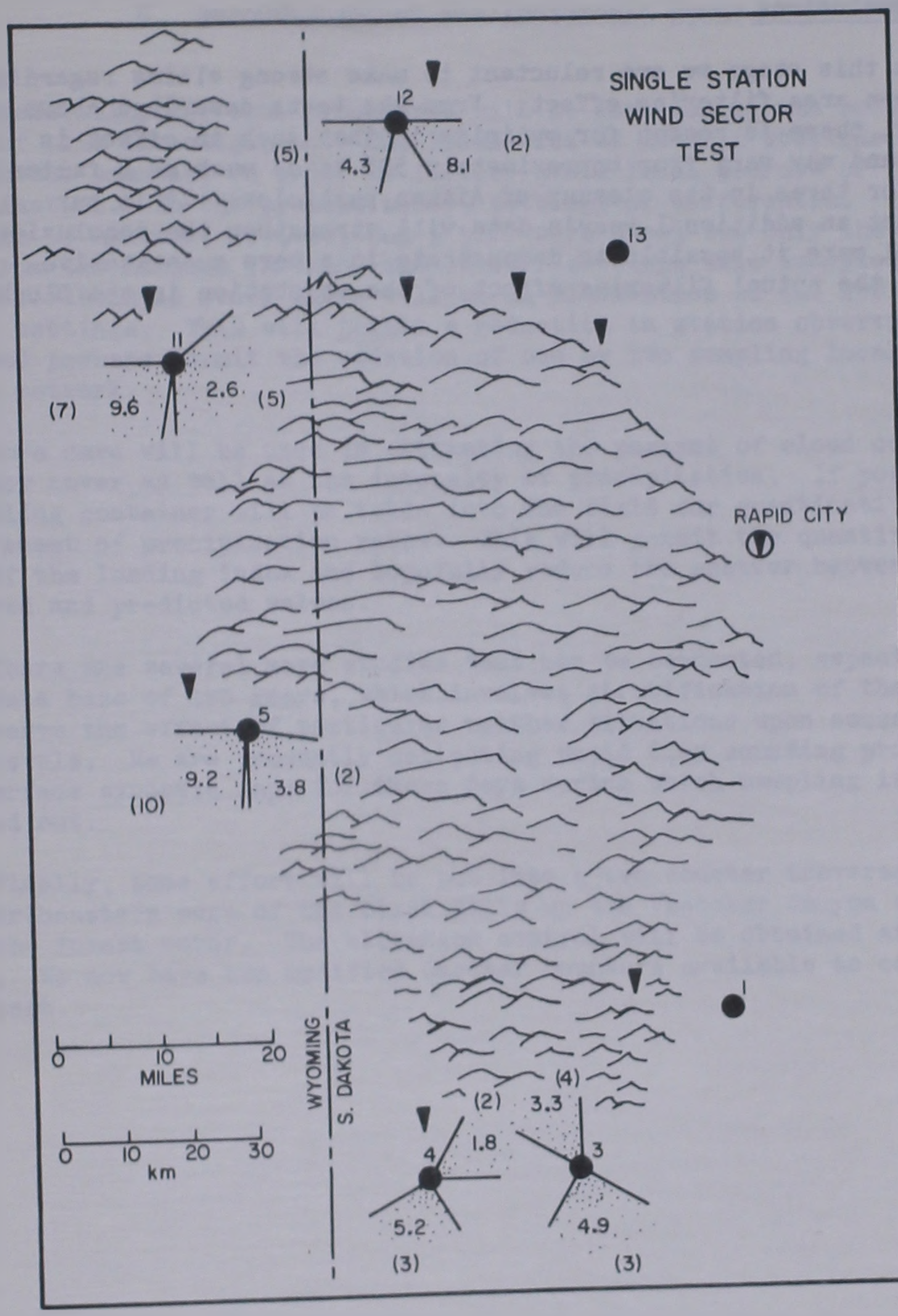

Fig. 22. Opposing (single station) wind sector test for five Black Hills SEAM stations. Sample size given in parentheses above each wind sector, and concentration in units of 10^3 cm^{-3} given within wind sector.

4.3 Conclusions

At this stage we are reluctant to make strong claims regarding the green area filtering effect. From the tests described above, however, there is reason for optimism in that such an effect is likely and may vary from approximately 50% to as much as a factor of two or three in the cleanup of Aitken particles. It is our hope that an additional year's data will strengthen the conclusions and will make it possible to demonstrate in a more quantitative measure the actual filtering effect of the vegetation in the Black Hills.

5. RECOMMENDATIONS FOR ADDITIONAL STUDY

Essentially the same procedures will be used during the second phase of this investigation. The localities of several stations will be adjusted somewhat in order to further avoid local sources of contamination. In the present study, settings of differential pressure of maximum, 100, 10, and 5 torr were used, but only the data from the maximum (Aitken) and 10-torr settings were analyzed. In the forthcoming study there will be an elimination of the 100 and 5-torr settings. This will permit a reduction in station observation time and perhaps permit the addition of one or two sampling localities to the network.

More care will be used in estimating the percent of cloud cover and snow cover as well as the intensity of precipitation. If possible, a sampling container will be taken into the field for quantitative measurement of precipitation rates. This will permit the quantification of the loading index and hopefully reduce the scatter between observed and predicted values.

There are several more studies that can be conducted, especially on a data base of two years, which involves stratification of the data to observe the effect of particular weather situations upon concentration levels. We are presently collecting Rapid City sounding profiles and surface synoptic maps for those days during which sampling is carried out.

Finally, some effort will be put into a two counter traverse from the northeastern edge of the Black Hills up the Vanocker Canyon area into the forest cover. The elevation control will be obtained at Bear Butte. We now have two modified Gardner counters available to conduct this test.

6. GENERAL CONCLUSIONS

There are several conclusions that have resulted from this study in addition to those stemming from the green area analysis given in Section 4 above. One of the major conclusions that can be reached is that the Black Hills area of the northern Great Plains contains some of the cleanest air available in the United States. For example, according to the data of Landsberg (1938), the average mountain concentration in the interval 1000 to 2000 meters is 2.13×10^3 particles per cubic centimeter. The geometric mean concentrations obtained in this study for the three central hills stations (8, 9, and 10) are 1.35, 1.44, and 1.87×10^3 cm^{-3}. Aitken counts as low as 150 per cubic centimeter have been observed during periods of high scavenging in the Black Hills. A typical urban count for similar sized nuclei will be in excess of 10^5 particles per cubic centimeter. It must also be remembered that the Landsberg data were collected over thirty years ago and concentrations in most areas have risen sharply.

We have also noted in this study several correlations of concentration having very significant confidence levels. These include trends with wind velocity, elevation, temperature, and precipitation intensity. The derived loading index can be used to predict the expected concentration of these particles (and hence, a general pollution level) given forecasts of simple meteorological parameters.

The green area effect has been demonstrated to be significant, but must be accepted at this time with caution in view of the restricted data base used in the analysis. We have learned that applying tests to reveal the reality of the green area effect requires a careful elimination of pollution sources and a consideration of the natural decrease in count with elevation, as well as the presence of scavenging processes.

There is an additional advantage in having completed such a study and in continuing the sampling program for several years in the future. The impending development of the coal resources in northeast Wyoming and southwestern Montana is now well known. Large scale development of power plants and coal gasification plants has already begun and the present shortage of energy supplies throughout the free world points to the continued development of coal resources. We are therefore providing a base line upon which to make future assessments of the increases in pollution derived from these sources.

ACKNOWLEDGMENTS

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